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The 3D Acid Test: Perceptual Attributes vs Renderable Elements

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The 3D Acid Test:

Perceptual Attributes vs Renderable Elements

Kathryn Wehrle

Submitted to the Faculty of Film, Art and Creative Technologies in candidacy for the
MA Degree in 3D Animation DL920

Submitted August 31, 2020

Declaration of Originality

This dissertation is submitted by the undersigned to the Institute of Art Design & Technology, Dun Laoghaire in partial fulfilment of the examination for the MA 3D Animation. It is entirely the author's own work except where noted and has not been submitted for an award from this or any other educational institution.

Kathryn Wehrle

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Abstract

The Romantics artificially embellished light and colour to convey emotion in their artworks. Light and colour were used to ignite a sense of enchantment and to stir an emotional response from the viewer. 3D software operates within this established visual tradition: current digital artistic representation involves a similarly embellished reality. This is a testament to what we continually want to see and how we would like to be visually entertained and informed, and physically based 3D renderer Arnold provides the tools for this continuation. Inherent in the world's most-used 3D rendering programme Arnold are light and surface attributes which have been programmed to be adjustable to achieve myriad visual results. These attributes, however, have a history rooted in computer graphics' plight for realism by abiding by the laws of optics and physics in their creation. However, these tools were designed with an arbitrarily chosen set of limits: arbitrary in the sense that these limits define a range of possibility to be used conveniently by the artist rather than by necessity or intrinsic nature.

Johann Goethe (b. 1749), a Romantic poet, was critical of how light and colour were used by his artistic peers. He was dissatisfied by the embellishment of light and colour in paintings, and endeavoured to know exactly what was happening when he looked at things. Goethe conducted a series of experiments on light and colour, which resulted in his book *Theory of Colours* (1810, trans. Charles Eastlake, 1840).

In my study, using *Theory of Colours* as a guideline, I have recreated fifty of Goethe's experiments in 3D. I explore the fundamentals of Arnold as it was created, revealing the

benchmark of current achievable 3D realism. Ten of these experiments are discussed in this

paper. These experiments, in my judgment, are more applicable to the scope of phenomena

replicable with a renderer, and scale the vast number of Goethe's experiments in *Theory of*

Colours to a reasonable set of testable conditions. The human perception of reality is the

baseline against which rendering qualities must be judged, and Goethe's experiments are

replicable.

As an instructor of 3D rendering, I aim to instill in my students the knowledge gained from this

study, with the intention to empower the students with their own rendering so that they may

make informed, predictable decisions.

The results of my study include the history of computer animation, the inception of Arnold's

foundational principles and their current use, and the story of Goethe and how he arrived at his

quandary.

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Introduction

I am a Computer Animation industry professional and instructor of 3D animation and rendering. My post-graduate diploma in Computer Animation followed the obtaining of my bachelor of Studio Fine Art. I credit this schooling for instilling in me a personal aesthetic and sensibility for 3D rendering and its capabilities. The instruction I received on the history of art as part of my studies has given me a well-rounded understanding of art's place and use within historical and procedural continuums.

My concerns as an instructor stem from the tendency for the uninformed artist to waste time in the rendering process.[1] Random troubleshooting does not provide the artist with adequate understanding for 3D rendering, but it is not the artist's fault. These days, 3D rendering is designed with tools that can be dialed around to achieve countless realistic results. Physically based rendering, which treats light in a scene the way photons behave in reality, is more of a concept than a strict set of rules, affording individual preference of the use of light and colour.[2] As an educator, I feel that arbitrary freedom hinders understanding: not only of 3D rendering but of the laws of physics on which 3D rendering programs are built, creating a wholly disadvantageous situation in the long run.[3] I believe that proper education on the subject of 3D

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[1] Kaorur32 (username). "Maya, rendering takes long, please teach me~" [sic]. *forums.cgsociety.org*, Original poster, May 2003, Accessed August 2020 ; ozelgoktug (username). "My Batch Render takes very long time" [sic]. *simplymaya.com/forum*. Original post on active thread, October 2015, Accessed August 2020

[2] Russell, Jeff. "Basic Theory of Physically-Based Rendering." marmoset.co/posts/basic-theory-of-physically-based-rendering. May 2020, Accessed August 2020

[3] "Physically based techniques attempt to simulate reality; that is, they use principles of physics to model the interaction of light and matter." Pharr, Matt et al. "Physically Based Rendering: From Theory to Implementation" *pbr-book.org*. Third Edition: October 2018, Accessed August 2020

rendering involves a thorough investigation of it through the lenses of history and technology within the continuum of science and art: the pillars on which 3D computer graphics (CG) was built. As says animation historian Tom Sito, "Writing the history of CG is not tracing a chronicle year by year as much as sewing a quilt".[4]

In this paper, I will present the situation of realism as trend, and the push for it by the demands of the consumers of the entertainment industry. Example of this is the effects industry with science fiction films such as *Jurassic Park* (1993) and the necessity for realism of the dinosaurs.[5] With physically based rendering programs such as Arnold allowing for hyper-realistic images, I am curious to see where we are with its ability for realistic interpretation as originally intended. Arnold is a unique departure from the entirely abstract defaults of traditional renderers.[6] I will discuss the continuum of how Arnold came to be by explaining its origins in computer science and optics.

I began teaching 3D rendering in 2017, the same year that rendering experienced a breakthrough. Arnold, a physically based renderer, joined with Autodesk Maya, the 3D industry standard used across the world from Hollywood studios to classrooms. Physically based rendering uses realistic material and light attributes to accurately represent real-world phenomena. Arnold does this by presenting with an arbitrarily chosen set of limits. They are

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[4] Sito, Tom. "Moving Innovation: A History of Computer Animation." *The MIT Press*. 2013. p. 3
[5] "Jurassic Park". Dir. Stephen Spielberg. *Amblin Entertainment*. 1993. Film
[6] heavymetalfox (username). "Arnold vs other renderers" [sic]. *forums.cgsociety.org*. Original post on active thread. March 2017. Accessed August 2020

arbitrary in the sense that the limits of the tools define a range of possibility. Arnold is

designed for artists. Good workflow for an artist involves easy, quick, and obvious access of a

tool needed. Arnold's tools are organised through a series of menus and tabs that are designed

to work seamlessly in conjunction with Maya's existing layout, workflow, and user experience.

Arnold's digital palette: surface, lighting, and rendering tools have been designed to encourage

the user's artistic license. They feature most-used functions prominently, such as the colour of

an item, or the intensity of a light. Attributes for nearly all tools present as sliders as their

method of user interaction. Clicking on the colour attribute summons a colour wheel with hue,

saturation, and value properties presented as sliders that can be conveniently dialed up or

down, encouraging troubleshooting. To assist in this and all rendering in Arnold is the Arnold

RenderView: a real-time interactive window on the screen that renders the image at the point

of adjustment of any attribute.

To explain further exactly to what extent Arnold is designed for artists, below is an image of

Arnold's surface properties window. A tool which is adjustable as a slider but also provides

real-world values is Index of Refraction, or IOR. Refractive indices describe how fast light

moves through a material. In Arnold, when interacted with, the tool presents a menu with a list

of materials of known indices of refraction. Later in this paper, I examine Arnold's abilities in

handling refractive phenomena, as it is a prominent real-world occurrence. Arnold's IOR tool

not only presents with scientifically calculated values, but also as a slider, and as a field for

numerical input. This makes reality one of three options. Light in a vacuum has a known IOR of

1. The material with the highest-known IOR is the mineral Germanium, with an IOR of 5.69.[7]

The numerical field however can allow numbers to be inputted as high as the billions, and

eventually infinity; or "inf". Theoretically, there is no limit to IOR because the more that light

can be slowed, the higher the refractive index will be. This limitless shader treatment indicates

the equally limitless treatment of light in the Arnold toolset.
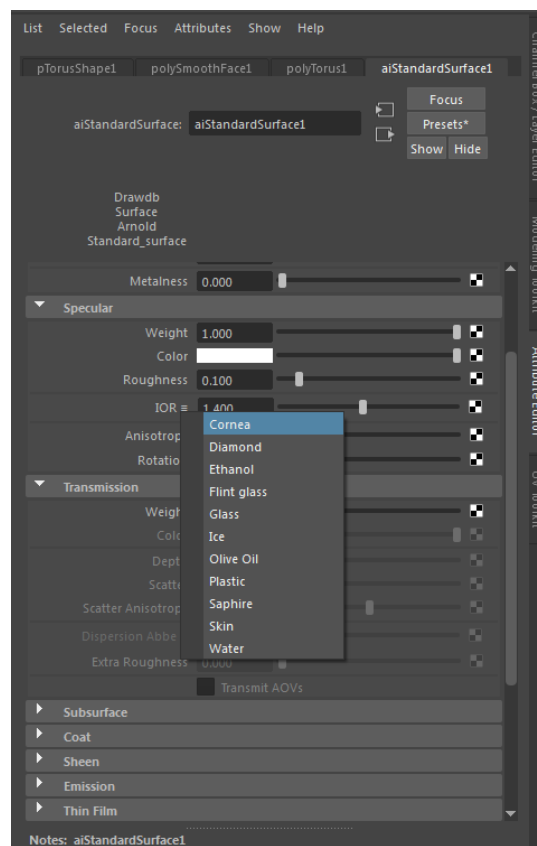
Fig. 1. Screen capture, *Arnold's Surface Properties window I*, Autodesk Maya 2019

Arnold's tools embody a certain tension between science and art. Artists are using a scientific

tool, but as artists and not scientists. Below is a still from the movie *Cloudy with a Chance of*

Meatballs II from 2013, one of the first feature-length films rendered with Arnold.

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[7] M. Polyanskiy, "Refractive index database," https://refractiveindex.info. Accessed August 2020

Fig. 2. Film still, *Cloudy with a Chance of Meatballs II*, Sony Pictures Animation, 2013

Fig. 3. John Constable, *The Hay Wain*, 1821

The Romantic painters evoked emotion by drawing the viewer into a phantasmal realm, establishing a visual vocabulary used today by 3D students, artists, and directors in the making of modern media. What emotional fantasy we experience in *Cloudy with a Chance of Meatballs II* we experience in John Constable's *The Hay Wain*, painted in 1821.

Constable was not only depicting a pond, a dog, nor the tree; he was manifesting a stylized ideal expected by the viewer: an experience contemporary with the expectations of his era. In the 3D scene, we are led to share in the experience of the characters peering over the edge of the hill, revealing the landscape presented directly to the viewer. This implies a viewer. Constable's art was rendered with paint, where Arnold renders the animator's art with pixels. The possibilities of colour for both artists have been leveraged and both are leveraging the ability of their mediums to enhance reality.

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Johann Goethe, German poet and naturalist, was dissatisfied with the arbitrary use of light and colour by his contemporaries.[8] Over forty years, he catalogued real-world examples of how light and dark interact to give birth to colour. His book *Theory of Colours* encapsulates these replicable findings against which we can test a renderer such as Arnold. By prototyping a set of experiments Goethe conducted on the real world and recreating it in Arnold, I hope to establish a baseline against which to inform students on their use of light and colour in 3D rendering so

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[8] Goethe, Johann. "Theory of Colours" 1810. (trans. Charles Eastlake, 1840). *The M.I.T. Press.* 1997. paragraph 134

that rendering will make sense and they will make informed choices within the arbitrariness offered by the abstract capabilities of Arnold's tools.

My attempt with the results of my study is to educate my students on the attributes of Arnold's lights and materials at their base functionalities, with the hope that the constant troubleshooting that tends to go with rendering can be reduced with the understanding of how light and material surfaces came to be, and how they work together to render a final image that can be anticipated. It is my concern as an educator that my students understand these intricate functionalities not only for the elimination of rendering guesswork, but also to gain knowledge in their historical place within the development of 3D computer graphics.

Often, artists through history were required to adhere to a style not their own for the sake of patrons, especially in the Italian Renaissance, and today this is also the case for artists entering into the industry of 3D animation.[9] The concept known as the "period eye", devised in the early 1970's by British art historian Michael Baxandall, describes that art from the Italian Renaissance was created and understood under cultural conditions:

"The public mind was not a blank tablet on which the painters' representations of a story or person could impress themselves; it was an active institution of interior visualization with which every painter had to get along. In this respect the fifteenth-century experience of a painting

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[9] Cohen, Alina. "In the Italian Renaissance, Wealthy Patrons Used Art for Power". www.artsy.net/article/artsy-editorial-italian-renaissance-wealthy-patrons-art-power. August 2018, Accessed August 2020

was not the painting we see now so much as a marriage between the painting and the beholder's previous visualising activity on the same matter".[10]

Since the early 15th century, several theories and methods of Italian colour and light use were put into practice, often together, and these styles kept their unique momentum through the ages. Some of the early notions were conceived not only by theorists but of the artists themselves. In the Notes section at the end of *Theory of Colours*, Goethe writes of painting philosopher Lodovico Dolce, citing Titian's tendencies in his book *The Dialogue of Painting*: "...Agreeable colours to the eye: ...grey next to dusky orange, white next to flesh-colour".[11] Artists of Venetian origin such as Bellini used colour to highlight clearness and fulness, which was criticized by Florentine Leonardo da Vinci for overlooking what he thought was of greater importance: chiaroscuro.[12] In Rome, Raphael was exaggerating the colours in his paintings to a near-glow effect, seen most obviously in his fresco *The Expulsion of Heliodorus from the Temple*. These differences in style were not simply a matter of individual genius; Italian painting for many was dependent on an artist-patron relationship. Patrons preferred unique styles and palettes, and the artists would be contractually required to adhere to them.[13] In addition to this, many of these great painters took on proteges, adding to the continuum.

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[10] Baxandall, Michael. "Painting and Experience in Fifteenth Century Italy". *Oxford University Press*. 1988. p. 45
[11] TOC, *Note C*, p. 362, from Dolce, Lodovico. "Dialogo Di M. Lodovico Dolce, Nel quale si ragiona della qualità, diversità, e proprietà de i colori. Con Privilegio". (trans. W. Brown, London). 1770
[12] Leonardo da Vinci, "Trattato della Pittura" (trans. John Francis Rigaud). London. 1835 https://archive.org/stream/davincionpainting00leon/davincionpainting00leon_djvu.txt pp. 85, 134. Accessed August 2020
[13] "...even as the artist was beginning to develop his personal and unique style, he still responded to the desires of his patrons" (of Raphael), Barris, Roann. "Raphael and the "Classical" Spirit of the Renaissance". *Perfecting and Surpassing the Renaissance; radford.edu.* July 2008. Accessed August 2020

The same can be said today about the visuals of digital media. Styles established by the

director or preferred by the audience must be adhered to, and often these styles are so

unnatural that we have become accustomed to expecting them. An example, the influence of

cartoons and anime contribute immensely and are completely unreal and fantastic compared

to natural colour perceptions, yet are grossly popular and influential. Green screens in place of

real-world sets anticipate a realistic default. Computer graphics are currently designed to

encourage the creation of infinite styles, bringing us further away from both the representation

of reality and how 3D programs were originally designed – as completely abstracted from

reality.

The motivation for the writing of *Theory of Colours* came from this same concern. Goethe

strove to understand light's behaviour in nature by taking on a thorough examination of it – by

exploring phenomena such as refraction, reflectivity, the nature of the rising of colours in

prisms, and the natural perceptual phenomena of atmospheric gradation. Goethe combined

previous historical theories on such phenomena with his own personal artistic sensibilities and

opinions, wholly immersing himself in his study. Goethe's documented experiments and notes

on his findings became his famous book, and at the end of his life, what he claims as his

greatest achievement.[14] This will be framed later in this paper where Goethe's observations of

phenomena are recreated as part of my study. In my study, I will follow Goethe's experiments

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[14] As Goethe recalls to Johann Peter Eckermann: "As to what I have done as a poet… I take no pride in it… but that in my century I am the only person who knows the truth in the difficult science of colors – of that, I say, I am not a little proud, and here I have a consciousness of a superiority to many." Goethe, as recalled by Eckermann, Johann. "Conversations of Goethe". (tr. John Oxenford). *Smith, Elder & Co. London.* 1930. p. 302 archive.org/details/conversationsofg01goetuoft/page/n5/mode/2up. Accessed August 2020

as he eloquently described them in my attempt to understand Arnold as it was created. How does Arnold measure up?

I will use Arnold's tool attributes as they are designed: based on the laws of physics and optics – to the best of my ability within the parameters – in capturing natural material aspects. In extending Goethe's methods, my interest lies in gaining a better understanding of Arnold's attributes and to what extent they accurately reflect physically based reality. I hope to take what I discover in this study back to my classroom. Adopting Goethe's methodology in understanding Arnold, removing my technical professional side and instead focusing on experiencing Arnold's attributes and render system in its attempt to recreate realistic optical experiences void of heightened reality we so often see today in 3D graphics.

My aim is to adopt Goethe's style of inquiry in this regard. Inspired by my own journey of art education, I will describe these findings. My output, along with this paper, will be a body of rendered frames and animations illustrating my discovered results as I explore the capabilities of 3D rendering program Arnold. In my extending of *Theory of Colours*, I will showcase ten animations which describe Goethe's most striking observations that still apply today in reality and in 3D graphics. As part of my conclusion, I will explain where my animations did not produce what Goethe saw, nor what we see when conducting the experiments with natural objects in the real world. This will delineate the shortcomings where Arnold still needs work to fully implement real-world capabilities expressed already 200 years ago.

Chapter One:
Realism as Trend and Romantic Thought

Since the early 2000s, most of my time in the 3D industry has been spent rendering images for children's television as a pipeline Technical Director. Kid's TV is well-known for its vivid and unnatural styles – many of the 3D characters are extraordinary in appearance, affording their designers a sky's-the-limit visual aesthetic, therefore relying on the arbitrariness of 3D tools. Typical also for these characters is that they be rigged to over-animate, providing them a caricature, pushing the entire look further away from reality and forging an aesthetic understanding between the viewer and the world of the character. This world – the director's choice – is also often somewhat simply constructed to allow for it to quickly carry the show's production through many episodes and seasons, creating a body and establishing a brand. Inevitably, these shows also cross the threshold into merchandise production, perpetuating the recognised style in different media from books to toys to cosplay. Society creates aesthetic demand, which informs technical implementations. Says Baxandall of this,

"A society develops its distinctive skills and habits, which have a visual aspect, since the visual sense is the main organ of experience, and these visual skills and habits become part of the medium of the painter: correspondingly, a pictorial style gives access to the visual skills and habits and, through these, to the distinctive social experience".[15]

Working in children's television brought me deep into the field of rendering synthetic images that can be silly and absurd. Like many of the painters from the Renaissance and beyond, I was contractually required to technically adjust from my personal aesthetic to the requirements of

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[15] Baxandall, p. 152

the embellished, fantastic visuals required to do my job. The tools in the 3D program that

created this look were required by me to be calibrated in such extreme ways that they would all

correspond and satisfy each other in order to be rendered into a polished cohesive frame. I

credit my experience in children's television for showing me a certain breadth of 3D rendering's

capabilities.

Fig. 4. Film still, *Bubble Puppy's Fin-tastic Fairy Tale*, Nickelodeon, 2012

This image, from the Nickelodeon series *Bubble Guppies* which I rendered, is a nice example of

this calibration. Bubble Guppies is a series which takes place entirely underwater. Here, we

see a fish witch with a castle and gloomy clouds, yet bubbles rising from screen left,

maintaining the underwater impression and overall aesthetic.

To achieve this aesthetic style requires technical implementation. The image of *Bubble Guppies*

has been adapted to meet the expectations of the audience as the show has a coherent style,

and this style relies on a technical implementation which has been defined by the demands of the audience. In the same way, *Cloudy with a Chance of Meatballs II*'s aesthetic and the implementation of its aesthetic are two things.

The heart of today's 3D hyper-realistic style comes from the way that light is rendered. In Arnold as in the real world, photons are emitted from lights, travel through the scene, and bounce off all surfaces at angles defined by the object or surface attributes. At the point of contact of a surface, information from that surface is calculated and carried to the next surface interaction along the photon's path, generating the natural effect of secondary lighting, or in 3D what is known as global illumination. Eventually, the photons end up at the camera. The arrival of potentially millions of these photons at the camera forms the rendered image. Even if it isn't a realistic look we're hoping to achieve, from a physics point of view, shaders describe how the surface interacts with the photons. Photons contacting a surface can appear absorbed, reflected, refracted from the surface, or scattered around inside the object. This type of rendering is called path tracing, in reference to the photons and their travelling about.[16] They provide hyper-realism because their behaviour is written to model reality with components which are abstract. Even the diffusion of light from its source of emission over a distance will dissipate in a natural fashion known as quadratic decay. Through the process of rendering, light from created setups also computes the natural expectation of shadows. Indices of refraction will calculate but like all shader attributes can be arbitrarily adjusted, forcing a

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[16] Photon mapping. More at: Georgiev, Iliyan et al. "Arnold: A Brute-Force Production Path Tracer". *ACM Transactions on Graphics Vol. 37 No. 3* p. 32. August 2018, Accessed August 2020

surreal splay of light demanded by modern synthetic media. Complex real-life light effects such

as caustics can be enabled or disabled with a button.
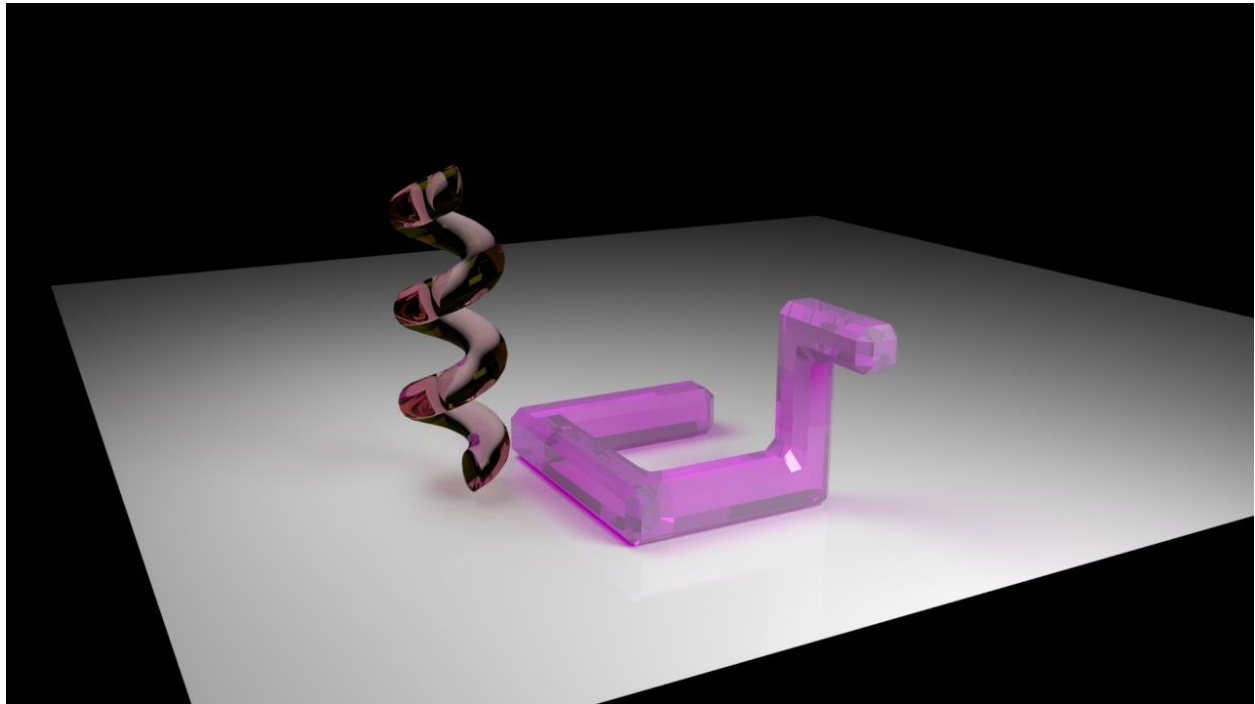
Fig. 5. Film still, *Arnold beauty pass*, created by the author, 2020

This image created and rendered by me is from a class I teach which showcases Arnold's

material and light interactions discussed above, and the influence of the objects on each other.

This is a good example of glassy attributes, global illumination, and light's quadratic decay seen

in its dissipation away from the source.

AOVs (Arbitrary Output Variables) present as a list of all material attributes and their

contributions during the rendering process. From a drop-down menu in Arnold's render

settings, these explicit arbitrary layers and their functionality can be isolated for compositing

and further postproduction to globally exaggerate the attributes. Another term for an AOV is a

render pass.

Fig. 6. Film still, *Arnold specularity pass*, created by the author, 2020
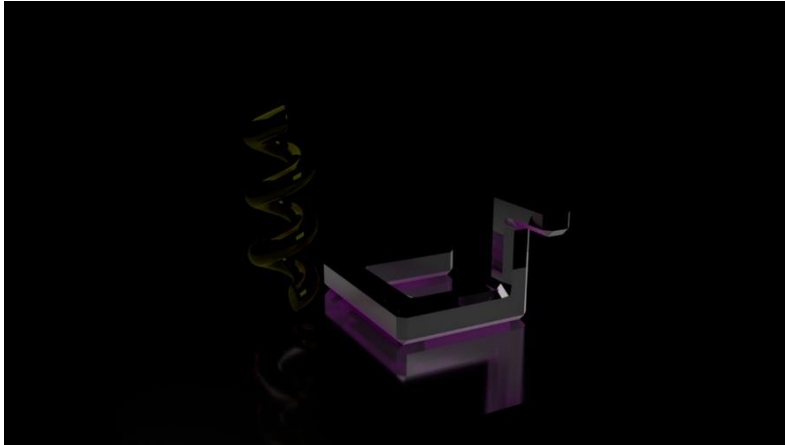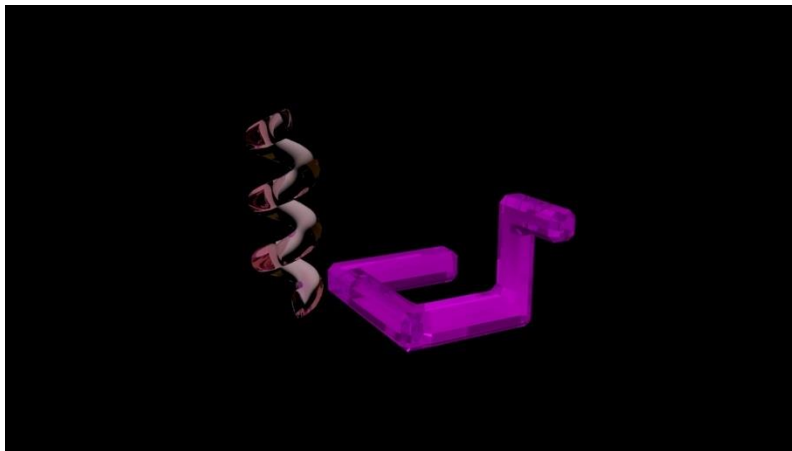

Fig. 7. Film still, *Arnold transmission pass*, created by the author, 2020

The first image demonstrates the isolated specularity attributes. The second image

demonstrates the isolated transmission attributes.

Most of today's CG-based entertainment presents to us as uncannily familiar and realistically

recognisable, but often with a twist. Slightly boldened hues or shimmering surfaces reflecting

fantastically are examples of this, but we ingest what we see as normal; today's graphics are

calibrated to our vision of reality and we have come to expect this look. Hence, an industry of

directors and artists exists in the generation of this style, thus requiring a field of computer

programmers working to broaden the capabilities of 3D renderers, establishing the trend.

Realism in entertainment graphics began as a necessity for believable-looking elements to

match live-action characters and sets for legitimacy and wow factor. So continues the case for

this in genres such as science fiction and fantasy: fields that have always strived to effectively

portray the existence of the unreal. Beginning with the 1976 film *Futureworld* as the first use of

graphics in film, the integration of CG technology was amplified.[17] Over time as the field of

graphics increased in sophistication, so began the building of studio production pipelines to

allow for the integration of computer graphics, leading to 1994's *Toy Story*: the first full-length

movie made entirely in 3D.[18] *Futureworld*'s mandate for the use of CG was so that the digital

hand and mask of the main character would look real. *Toy Story*, intended to entertain and not

convince us that toys can talk, effectively delighted our senses with believable shadows,

realistic lighting for times of day, and the variety of materials on the objects and characters.

Toy story's "realism" amplified even further the use of computed graphics in media, which is

extended even further today as styles develop.

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[17] "Futureworld". Dir. Richard T. Heffron. *Aubrey Company/Paul N. Lazarus III*. 1976. Film
[18] "Toy Story". Dir. John Lasseter. *Pixar Animation Studios*. 1994. Film

The trends in realism today are at their base the same aesthetic as those of kid's TV; they are built on the arbitrariness of attributes in CG programs, perpetuating a hyper-real style. Rendering encompasses the absurdity required for children's entertainment as well as complex realistic looking special effects elements interwoven with live action. Dragons being ridden by humans appear uncannily real because they shimmer and appear animalistically complex. A tidal wave taking over Times Square is believable because it reflects and washes through the streets with an appearance we believe. As viewers, we are awestruck, and we want more, in turn, pushing 3D programmers further into creative ways to arbitrarily utilise the capabilities of new generations of renderers such as Arnold which consider real-world optical phenomena. Arnold's sophistication for generating embellished looks relies on its state-of-the-art technical capabilities of simulating natural light, affording these unlimited realistic styles.

A current trend is the use of game engines such as Unreal and Unity. Real time animation is incorporated into studio render pipelines, providing an affordable alternative to real production costs requiring physical sets.[19]

Studios that have incorporated physically based rendering pipelines have hired look-development teams. With the efficiency of physically based rendering comes the Pandora's box of being able to push reality and create 3D characters and situations never before seen. Interestingly, there were drawbacks to some aspects of this approach – perhaps an argument that we are not yet fully arrived at a place where graphics can wholly imitate reality. For

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[19] Failes, Ian. "Upcoming Animated Series 'Zafari' Is Being Rendered Completely with The Unreal Game Engine". *cartoonbrew.com*. www.cartoonbrew.com/tools/upcoming-animated-series-zafari-rendered-completely-unreal-game-engine. December 2017. Accessed August 2020

example, look development artists had to generate the appearance of atmosphere and gradation of environment in landscape scenes because of the arbitrariness of 3D space itself. Arnold comes equipped for this issue with plug-ins for environmental fog and depth of field, to be added in compositing.[20]

Leonardo da Vinci was the first to implement atmospheric perspective in his 1503 painting *La Joconde* (*Mona Lisa*), but even his use of it was arbitrary in the sense that although da Vinci could not fully explain what he observed, he included it in his painting, showcasing what he saw as he looked into the distance. It was very effective and was perpetuated by many artists after him.[21]

The two images *Cloudy with a Chance of Meatballs II* and *The Hay Wain* are both stylized for the expectations of the audience. These expectations determine the stylistic content of these images. Likewise, Constable had to paint in conformity with his patrons' expectations. This style is hyper-real in the literal sense. Romantics were interested in an objectively realistic world, but used hyper-realistic representation. The same can be said for 3D software. Arnold does this in a contemporary environment. *Cloudy with a Chance of Meatballs II* and *The Hay Wain* strive beyond realism – they are a sort of mediated realism. Idealised realism in *The Hay Wain*

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[20] Fahim, Erini. Personal interview. March 23, 2020
[21] "…a subject that was to fascinate Leonardo for the rest of his life… is the near-precision of linear perspective and the way the atmosphere blurs the distant horizon, an optical phenomenon that he would later call "aerial perspective"." Isaacson, Walter. "Leonardo da Vinci". *Simon and Schuster*, October 2017. p. 48

embodies a different set of cultural expectations but is still believable. The style continuum informs the technical continuum, where the past informs the present.

Romantic Thought

Characterised by emphasis on emotion and influenced by radical thought, the Romantic artistic movement was rooted in the Sturm und Drang period from which Goethe was a literary pioneer with his titular novel *The Sorrows of Young Werther*. This book written in 1774 tells the tale of unrequited love through a series of love letters. Upon its publication, Goethe, previously unknown as an author, became an instant celebrity. Like the popular influence of Kurt Cobain's death, *The Sorrows of Young Werther* had a wide cultural impact.[22] Europeans grew insatiable for this emotionally heightened entertainment. "Werther Fever"'s cultural impact was so great that men were dressing in the style of the main character.[23] "It was widely believed that Goethe's work led to a wave of young men deciding to end their lives all over Europe, many of whom were … using similar pistols. Some even had the copies of the novel beside their bodies with the page opened to the page of the suicide scene".[24] Sturm und Drang preferred emotion to the rationalism of the Enlightenment. Romanticism promoted individual imagination; "The artist's feeling is his law… the artist should not only paint what he sees before him, but also what he sees in himself".[25]

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[22] Jobes DA, Berman AL, O'Carroll PW, Eastgard S, Knickmeyer S. "The Kurt Cobain suicide crisis: perspectives from research, public health, and the news media". *Suicide Life Threat Behav*. 1996. 260‑271
[23] Goleman, Daniel (March 18, 1987). "Pattern of Death: Copycat Suicides Among Youths". *The New York Times*.
[24] Devitt, Patrick. "13 Reasons Why and Suicide Contagion". *Scientific American*. Accessed August 2020
[25] Caspar David Friedrich, Romantic artist (b. 1774, Germany)

Resonating the theme of torment experienced by poor Werther, nightmares were a common

subject of paintings from the period. Here, *The Shepherd's Dream* painted in 1793 by Swiss

painter Henry Fuseli represents the realm of dreams, fantasy, and imagination typical of Sturm

und Drang.

Fig. 8. Henry Fuseli, *The Shepherd's Dream, from Paradise Lost*, 1793

It was believed by the authors and artists of the time that the content of their work had to

come from their own imagination, with as little interference as possible from "rules" dictating

what a work should consist of.[26] Originality was essential. Order from the Enlightenment was rejected in favour of mystical representation full of emotion, as evoked in Constable's *The Hay Wain*.

The study of optics as pursuit in the late eighteenth century was arguably more a concern of the preceding Age of Enlightenment, however Goethe's approach which emphasised the experience as aesthetic was typical of the general modes of Romantic-era thought, and typical in general of early nineteenth century thinking in Europe. The study of politics, optics, and art were united in the continuum of history of science and the nature of understanding.

"The renouncing of life and immediacy, which was the premise for the progress of natural science since Newton, formed the real basis for the bitter struggle which Goethe waged against the physical optics of Newton. It would be superficial to dismiss this struggle as unimportant: there is much significance in one of the most outstanding men directing all his efforts to fighting against the development of Newtonian optics."[27]

Goethe's attitude toward knowledge and the understanding of things is that there is a certain enjoyment with the engagement of learning, resulting in a formation of an intimacy between the observer and the subject of study. Goethe lived his life with authentic passionate curiosity,

[26] Leidner, Alan C. "Titan in Extenuating Circumstances: Sturm Und Drang and the Kraftmensch". PMLA, Vol. 104, no. 2. www.jstor.org/stable/462503. 1989. p. 178. Accessed August 2020
[27] Werner Heisenberg, during a speech celebrating Goethe's birthday. Lehrs, Ernst. "Man or Matter", Chapter II

and the basis of his questioning of natural phenomena arrived from his spirit of understanding

based on personal experience.

Chapter Two:
Goethe

The peacefulness of the Italian countryside was believed by Goethe to embody a serene respite away from the popularity he gained from *Werther*, and the ornamental and theatrical Baroque and Rococo movements which had recently flourished across the continent. Goethe's passionate and delicate temperament was looking for surrender amongst the southern Italian landscapes and antiquity, and he made the journey there in 1786. Through what he had seen in paintings, Goethe developed an aesthetic fascination with Italy and its Neoclassical style. Almost as though he was seeking paradise, Goethe surrendered himself upon his arrival in Rome, an experience he described as "being born anew". As he cited in his travel journal *Italienische Reise*, it was through what he wanted to see for himself in Italy that would develop in him a greater personal awareness. Goethe wrote of this seeking: "to discover myself in the objects I see."[28] In Italy, Goethe engaged in energetic conversations with several Neoclassical artists, including fellow Germans Tischbein and Kauffman who had by then established themselves in Rome. It seemed to Goethe that there were rules for practically everything concerning the medium, but none about the use of colour in painting. Nobody could give him satisfactory information as to the choices that were being made. In Goethe's time, the medium of painting was how everyone was experiencing the world. To learn that the use of colour and light was arbitrary and that there were no clear rules surrounding it in his paradise was troubling to him. It was this conundrum that drew Goethe to the determination of a basis or guideline for the use of colour in painting, and in 1788 upon his return to Weimar he began this inquiry.

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[28] Goethe, J. W. *Italienische Reise*. (trans. W.H. Auden and E. Mayer). *Penguin Books*. 1962. p. 57

Goethe said of painters:

"There are painters who, instead of rendering the colours of nature, diffuse a general tone, a warm or a cold hue, over the picture. In some, again, a predilection for certain colours displays itself; in others, a want of feeling for harmony".[29]

Goethe took on his investigation in an all-encapsulating way – with vigour and wholistic consideration. In my study, I will follow Goethe's experiments to the best of my abilities as he eloquently described them, in my attempt to understand Arnold as it was created. My experimental recreation of Goethe's findings uses modern tools that are largely based on similar observations of light. My aim is to see whether Arnold is capable of delivering the real-world results it promises. I will explore Arnold's tool attributes as they are designed to model the laws of physics and optics, to the best of my ability within the parameters. By following Goethe's lead in the reproduction of his experiments, I vow to remain faithful to their recreation and undertaking. I intend to use as little intervention as possible to see how well Arnold's tools do in recreating the optical effects Goethe describes. This extending of Goethe's book should provide a better understanding of how closely Arnold imitates reality in its physically based rendering.

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[29] TOC, paragraph 134

Chapter Three:
Technical Continuum

The style continuum informs the technical continuum. *Cloudy with a Chance of Meatballs II* relies on an enhanced reality as demanded by the audience. The aesthetic concept informs the technical decisions taken by the 3D artist. The specification to which Arnold has been written is informed by the demands for realism.

In order to educate my students on making wise choices in rendering, I believe confusion and needless time-consuming troubleshooting can be reduced with the understanding of how light and material surfaces came to be, and how they work together to render a final image that can be anticipated. It is my concern as an educator that my students understand these intricate technical functionalities not only for the elimination of rendering guesswork, but also to gain knowledge in their historical place within the development of 3D computer graphics.

Spectroscopy is the study of how light interacts with matter. All molecules absorb and emit light differently, based on what they are made of. Consider how we see things in nature: how things appear to us is due to the behaviour of light as it interacts with different surfaces. This allows us to discern what is what, where to go, what not to touch, what looks soft. Slippery ice and a soft chair appear very different to our eyes because of the way light is interacting with them. Light which interacts with a hard, glass-like surface will reflect from that material, causing a shiny appearance. In the case of the soft chair, light is absorbed by the matte qualities of its canvas. It is these differences in the appearance of things which concerned the forefathers of computer graphics to create surface properties to generate similar appearance and discernment. In the world of computer graphics, these perceptual phenomena have been

incorporated to form the foundation of physically based rendering. 3D surface attributes are designed for light.

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The field of computer animation had its beginnings in post-World War II America: a time which celebrated creation, economic expansion, and the beginnings of consumerism. Becoming a unique discipline of computer science in the mid 1950's, computer graphics served as visualisation aides for aircraft engineers and government workers. As computing technology developed, in the 1960's under the Advanced Research Projects Agency (ARPA), which recognised the potential for computer graphics as an aide to such governmental applications, special funding was allotted to institutions such as MIT and the New York Institute of Technology.[30] Given this exceptional financial circumstance and encouragement, computer graphics scientists were allowed the freedom of creativity and collaboration, and were able to set the foundation of graphics tools that we use today. The year 1967 saw the introduction of both geometry-based computer graphics and an early form of rendering. From the establishment of these two pillars, Cornell University founded its School of Architecture.[31] In 1968, scientist Charles Csuri, "the father of digital art and computer animation" used graphics technology to create a piece of art.[32] *Hummingbird*, considered the first animated film, reveals

[30] Rivlin, Robert. "The Algorithmic Image: Graphic Visions of the Computer Age". *"University of Utah*. www.cs.utah.edu/gdc/history/. November 26, 2000. Accessed August 2020
[31] "1967: Cornell University's School of Architecture is founded by Professor Donald Greenberg". Smith, Alvy Ray; Paul Heckbert. "History of Computer Graphics (CG)". *The Computer Graphics Book of Knowledge*. www.cs.cmu.edu/~ph/nyit/masson/history.htm. Accessed March 2020
[32] Trachtman, Paul. "Charles Csuri is an 'Old Master' in a new medium". *Smithsonian Magazine*. February 1995. Accessed August 2020

black lines which form the drawing of a hummingbird on a turquoise screen. That year, Csuri's

animation was purchased for permanent collection by the Museum of Modern Art.[33] This

appreciation and recognition by a major world-class fine art institution married government-

based technological research with scientists creating art.[34]

The early 1970's saw a boom in the commercial use of computer graphics as art-form.

Research at the time was focused on the continuation of representation of geometry-based

objects interacting in three-dimensional space. As in nature, we can see light only when it

strikes something. The surfaces of 3D objects therefore would require light to interact with

them such that their shape and form be discernable in 3D space for the purposes of modeling

and animation. Scientist Bui Phong (b. 1942), in 1973, developed a shader model for 3D

geometry allowing for such light-surface variance.[35] Phong's model involved the use of surface

normals. Surface normals of 3D geometry are vectors occurring perpendicularly on each face of

that polygon's mesh, and determine the way the surface of an object is facing (relevant toward

or against a light source), and describe the direction light's path would travel if it were to reflect

from the geometry. Typically, we are concerned with the normals facing outward, indicating

the side of the mesh that will respond to light and accommodate materials and maps for

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[33] Csuri, Charles. "Hummingbird." 1968. 16mm film transferred to video (black and white), 12 min.
The Museum of Modern Art, New York. Purchase, 1968. www.moma.org. Accessed August 2020
[34] Today, there is an arguable bias against animation as fine art. Institutionally, animation is a vocational field of study, almost entirely populated by visually inclined students looking to work in the field of entertainment such as film, television, and gaming. IADT, the world's first 3D animation master's programme, is perhaps testament that this is changing. The output of a graduate degree is what is often lauded by galleries of fine art: consideration, concept, politics, and research are almost of higher importance than the visual medium itself.
[35] Phong, Bui Truong. "Illumination of Computer-Generated Images". *Department of Computer Science, University of Utah*, July 1973. Accessed August 2020

rendering. The opposite side does not respond to light or any assigned values, typically

indicating the interior or underside of the mesh. Here is an image of a 3D surface (S), indicating
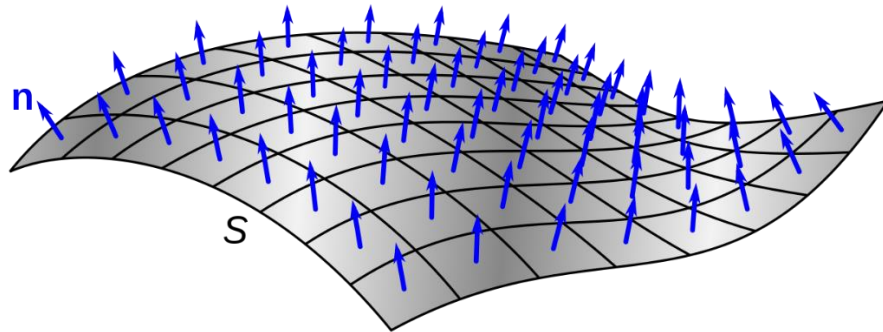
outward surface normals (n):

Fig. 9. Chetvorno, *Normal Vectors on a Curved Surface,* 2019

The year of 1973 was when the world's first SIGGRAPH conference was held.[36] At the 1976

conference, Scientist Jim Blinn (b. 1949) presented his model for the same purpose of 3D object

discernment.[37] Both Phong and Blinn shader models were written to rely on the real-world

phenomenon of specularity to provide their functionality. Each model renders specularity

differently due to how Phong and Blinn wrote their shaders to behave with surface normal

vectors, since the direction of the normal vectors describes how the 3D object will appear when

lit. The Phong model represents a glossier surface, and the Blinn model represents a soft

metallic surface such as brass or aluminum. Today, both Phong and Blinn shaders exist

eponymously as viable shader models for the representation of three-dimensionality and

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[36] Special Interest Group in Graphics, SIGGRAPH is a branch of the Association for Computing Machinery (ACM), the world's first and largest computing society. Yearly conferences are held. www.siggraph.org
[37] Smith, Alvy Ray; Paul Heckbert. "History of Computer Graphics (CG)". *The Computer Graphics Book of Knowledge*. www.cs.cmu.edu/~ph/nyit/masson/history.htm. Accessed March 2020

specularity. Currently, Maya users interact with these shaders daily as they are the standards of 3D representation established in the 1970's. Phong and Blinn shaders are two of the three foundational shader models of 3D graphics, the third being Lambert.

Johann Lambert (b. 1728) studied early concepts of the activity of light on different surfaces, and was particularly interested in the absorption qualities of light. He wrote of the absorbance of sunlight on different items in nature in his 1760 book *Photometria*.[38] Lambert made special note that raw, unfinished wood surfaces are the ideal model of diffuse light behaviour.[39] Lambert shaders in Maya's shader library exhibit perfect diffusion, and zero specularity attributes. Today, Lambert is eponymously remembered as the default material shader of all objects as they are created in Maya, making the Lambert shader the most used shader in the Maya library today.
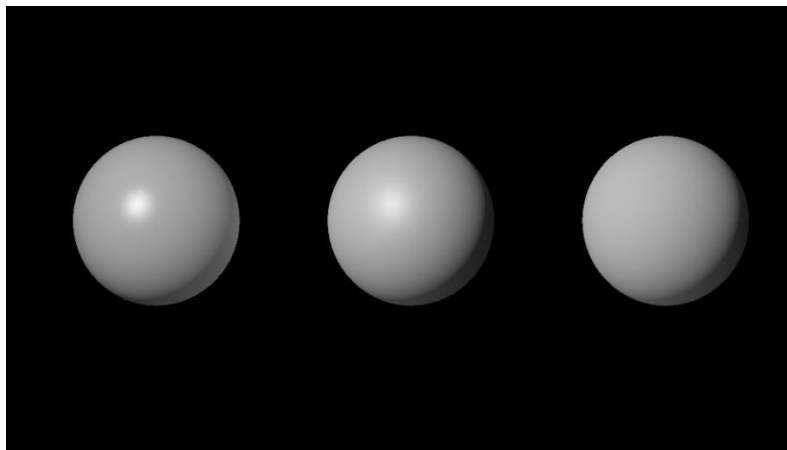

Fig. 10. Film still, *Maya Software render*, created by the author, 2020

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[38] Lambert, J. H. (1760) "Photometria, sive de Mensura et Gradibus Luminis, Colorum et Umbrae". (trans. DiLaura, D.L., "Photometry, or, On the measure and gradations of light, colors, and shade". *Illuminating Engineering Society*. 2001)

[39] "As already found by Johann Heinrich Lambert, various kinds of natural materials such as paper and uncoated wood have scattering characteristics". Paschotta, Rudiger. "Lambertian Emitters and Scatterers*". RP Photonics Encyclopedia*. www.rp-photonics.com/lambertian_emitters_and_scatterers.html. Accessed August 2020

From left to right: Phong and Blinn shaders showcasing specularity, and the Lambert shader showcasing diffusion.

Rasterisation is the earliest form of rendering and has been used to create digital images since the beginning of the 1960's.[40] In 3D graphics, rasterisation is a technique which converts scene geometry into pixels by scanning the camera's view against a projected virtual plane. The approach consists of an (often horizontal) scan-line analysis of the scene and generation of an image, row-by-row. Objects that are obscured by other objects in the direct path of the camera's analysis do not get considered in the final calculated image. Maya's inherent renderer, Maya Software, uses this approach, and the above image has been rendered using this technique. Scan-line rendering exists in Maya today as it excels at generating high-quality surfaces and textures from Maya's shader library, and can apply a Z-buffer (or depth analysis), against the virtual plane to decipher shadows. These features, however, in comparison to ray tracing, are also its limitations against real-world lighting scenarios.

Advanced realistic optical effects became possible when the behaviour of light in the real world was considered in the calculation of rendered images. This technique, ray tracing, garnered enormous success in its believability, as its functionality is to follow rays of light as they travel from the source to the camera, affording global illumination and realistic reflections: the birth

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[40] Smith, Alvy Ray; Paul Heckbert. "History of Computer Graphics (CG)". *The Computer Graphics Book of Knowledge.* www.cs.cmu.edu/~ph/nyit/masson/history.htm. Accessed March 2020

of physically based rendering. Mental Ray, a pioneer of this rendering technique, emerged in the late 1980's and was adopted by Maya as a counterpart to Maya Software's scan-line rendering in the early 1990's. Mental Images, the makers of Mental Ray, won an Academy Award in 2000 for Best Visual Effects used in the movie *The Matrix*.[41]

Credited for Blinn's Law, Jim Blinn stated in 2006: "As technology advances, the rendering time remains constant".[42] Not based on evolution of technology but on human patience, Blinn argues that as render times reduce, digital complexity rises, and after all the technological advancements through the years, render times are not getting any faster.[43] As research into ray tracing began in the 1980s, it was not until the 2000s when alternative methods of physically based rendering were gaining industry momentum. Adopting a method of data acquisition called the Monte Carlo method, billions of incoherent light paths were able to be integrated, unbiasedly describing light's behaviour in a scene, and to faithfully render global illumination and other realistic light phenomena.[44] The difference between the Monte Carlo's path tracing and Mental Ray's ray tracing is that Monte Carlo, in short, simulates better reality, and the behaviour of the light rays is more manageable, versatile, and arbitrary. The user would be able to control what aspects of the scene needed more or less light attention. Ultimately, the Monte Carlo method's physically based rendering provides the possibility for

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[41] Thacker, Jim. "Mental Ray: A Retrospective". *cgchannel.com*. November 20, 2017. Accessed August 2020 ; "The Matrix". Dir. Lana and Lilly Wachowski. *Warner Brothers.* 1999 ; Martin, Paul. "The Matrix Wins Four Academy Awards". *matrixfans.net*. March 3, 2000. Accessed August 2020
[42] Jim Blinn, quoted at SIGGRAPH in 2006
[43] Seymour, Mike. "Founders Series: Industry Legend Jim Blinn". *fxguide.com*. July 25, 2012. Accessed August 2020
[44] Lafortune, Eric. "Mathematical Models and Monte Carlo Algorithms for Physically Based Rendering". *Department of Computer Science, KU Leuven, Belgium*. February 1995, Accessed August 2020

faster render times, and allows the user full control of render parameters. This control of light's

behaviour in rendering is called sampling, and the more sampling that is finessed, a more

desired image can be rendered. In some cases, sampling can optimise render time, countering

Blinn's Law, and afford the artist a new way of engaging with render tools and parameters.

As render technology advances, throughout their career artists will rarely use only one

rendering engine. It is the trend for rendering styles to evolve previous functionalities,

integrate into software packages, and become established into studio pipelines only to become

obsolete as they are replaced. The overall idea in rendering, then, is to understand its

foundation with awareness that the tools will always change. Arnold utilises the Monte Carlo

method in its rendering, and in 2017, was integrated with Maya, eliminating Mental Ray from

its long-standing streak as Maya's ray tracing alternative to scan-line.[45] I believe it is useful to

understand this continuum, as the history and fundamentals of how Arnold came to be can be

used to our advantage in understanding where rendering may take us in the future.

The story of Arnold: Marcos Fajardo

Marcos Fajardo is the award-winning chief architect of Arnold. During his undergraduate days

in Spain studying computer science in the 1990s, the landscape of the workforce where he'd

inevitably end up seemed unappealing. Fajardo recalls computer science of the time "a bit dry,

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[45] Maestri, George. "Maya 2017: Goodbye Mental Ray, Hello Arnold!". *LinkedInLearning.com*. July 25, 2016. Accessed August 2020

very boring".[46] In the computing lab of his university, he found a book on graphics and models

of ray tracing along with open-source code which he downloaded and began investigating. It

was exactly the kind of code he was learning in school, but the difference was that the results

were fun – he could understand their applications more clearly because he could see the results

in pixels. "Everything was much more visual and less dry than what I was seeing on the

blackboard at university", he recalls.[47] The source code came with bibliographies pointing to

technical papers which he read and learned with delight. It was in the nights when he should

have been sleeping that Fajardo became an expert in path tracing. He started missing classes at

university because he would be awake all night with his new hobby. "My grades were going

down, I was failing at school, my parents were worried", but he was becoming a "crazy expert"

in something.[48] Fajardo barely passed university, and accepted his first job coding graphics in

Madrid. In 1999, when Fajardo was working as a researcher for a software company in Los

Angeles, he went with two friends to the Arnold Schwarzenegger film *End of Days* where his

friends imitated the Arnold accent, cracking up the audience. Fajardo had never realized what

a distinctive voice Schwarzenegger had, since he had only seen Schwarzenegger's films in Spain,

where they're dubbed in Spanish. One of Marcos' friends suggested "Arnold" as the name of

his rendering project he was working on. His quote was: "So I thought - what the hell - I will call

it Arnold, but I did expect to change it, but I never did".[49]

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[46] Nichols, Chris. "CG Garage". *stitcher.com*. Software engineer Marcos Fajardo, Episode 239, August 26, 2019.
www.stitcher.com/podcast/chaos-group-labs/cg-garage/e/63475541. Accessed August 2020
[47] Ibid.
[48] Ibid.
[49] Ibid.

Fajardo's experiments with ray tracing are akin to Goethe's experiments in the real world. Both

Fajardo and Goethe were tireless and inspired, and pushed the limits of the understanding of

their environments.

Chapter Four:
The Experiments

"To portray, rather than explain"[50]

Goethe approached his exploration into light and colour with a thorough, intimate, and pleasurable curiosity. He was not interested in the explanations that math or physics could provide; he was an artist who was inspired by what he saw. *Theory of Colours* is his encapsulation of experiments, accounts, and musings on light and colour, based on observations of nature, motivated by his artistic sensibilities. There were no rules governing the use of colour among Goethe's contemporaries, and he wanted to find consistent guidelines not subject to artistic whim. Goethe's motivations can be continued unbroken into the present, where there are still no rules governing the use of colour in rendering.

The human perception of reality is the baseline against which rendering qualities must be judged, and Goethe's experiments are replicable. Although the experiments comprise his views on the nature of light in how it is perceived, the simple tools and optical results are those which can be produced and appreciated in like manner. In this interrogation, I will reveal the dissonance between render and reality. Some of Goethe's experiments are casual after-thoughts on halos seen around the heads of friends while walking in a dewy meadow, while others are very formally introduced with details of all materials needed at their onset. The first three Parts of the book are the foundation of Goethe's observations, and discuss all topics constituting his experiments. Goethe qualifies the phenomena into sections such as Effects of

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[50] Miller, Douglas (October 1995). "Scientific Studies - Goethe: The Collected Works". *Princeton University Press*. Vol. 12, p. 57

Black and White Objects on the Eye, Coloured Shadows, and Grey Objects Displaced by

Refraction. It ought to be noted that Goethe was very exhaustive in his investigation. Several

of the chapters sectioned from the Parts contain multiple experiments proving the same

phenomenon. To illustrate Goethe's systematic organisation of *Theory of Colours*, here is an

image of his table of contents:

CONTENTS.

Fig. 11. Johann Goethe, *Theory of Colours Table of Contents p. xxxi,* (trans. Charles Eastlake), 1840

I have extended Goethe's systematic approach in my own working methodology. I maintain the categories obtained from perceptible reality, building up a truth table of Arnold's abilities against real life. What I've done is create a catalog of renderer abilities not specific to Arnold, but which can be extended across the family of renderers available today.

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The experiments I have chosen to create as 3D animations reflect to the best of my discernment those that are of Goethe's more formal variety. Several of the animations with moving components have been rendered over a 100-frame period. In classical animation, a walk cycle will normally require 24 frames, or one second, for each footfall.[51] This means a full two-step cycle is 48 frames, and so on. It is from this guideline engrained in me as an animation professional that I have chosen the round number of 100 frames for these animations. Often, I will repeat the 100-frame cycle three times for effect. Using my own sensibility, I have determined this length of animation to be appropriate in featuring each phenomenon to be observed, and thus I have applied this same length to all animations for the sake of consistency.

My fifty animations have each been rendered with text at their introduction, featuring Goethe's own words as he describes what we are about to see. Theory of Colours in 3D, what I have titled this compendium, can be viewed online, here:

vimeo.com/user/114655114/folder/1868931. The organisation of my animations corresponds

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[51] Gray, Rusty. (October 2017). "Walk Cycle Animation Blueprint: A How-To Tutorial". *rustyanimator.com*. Accessed February 2020

to that of Goethe's as they are divided and chaptered in *Theory of Colours*. I maintain the

numbering structure of Goethe's chapters in my experiments, listing them prefaced with

numbers 1 through 50, and the second number and name is as Goethe had chaptered them.

Appendices 1-3 contain my methodology in exploring Arnold's capabilities. In my creation of

Goethe's experiments, I decided to take away as much as possible from its arbitrary attributes,

to be consistent, and to remove variability by using the software in a stripped-down honest

way. This body of experimentation is where I made determinations on what the software is

capable of. Can Arnold reproduce what Goethe saw?

The entire written body of my experimentation is contained in **Appendix 1**, and is the core of

my research. Fifty of Goethe's experiments as he describes them and which I conducted in 3D

are in this Appendix. They demonstrate the kind of technical work that was required in my

creation of an organised rational set of investigations.

Appendix 2 is an Excel spreadsheet of the 3D ingredients that went into the creation of my fifty

animations, listing the ingredients and recipes of my investigative undertaking. The categories

of the spreadsheet detail all Maya components (horizontally) of the fifty animations, required

by their Parts and chapters (vertically).

Appendix 3 is a list of images of the fifty Maya scene files, in perspective view, showing scale

and continuity in my attempt at accuracy. It is to be noted that Maya has its own language of

distance measurement: Maya Units. Thus, several experiments contain the base model of a man, to help me maintain scale in my scene file construction.[52]

Ten experiments from the fifty are of particular interest, and are highlighted in the Appendix 2 spreadsheet in yellow. These highlighted animations can be viewed online separately from the compendium. Ten Highlighted Experiments, what I have titled these, can be viewed here: vimeo.com/user/114655114/folder/2435013. The organisation of these animations corresponds to that of the compendium; Goethe's organisation. I have chosen to exhibit these ten experiments in this paper as they put key attributes of Arnold's renderable offerings to the test, and showcase its ability or inability to duplicate Goethe's result. These experiments in my judgment were more applicable to the scope of phenomena replicable with a renderer, and scale the vast number of experiments to a reasonable set of testable conditions.

Whether or not the result was achieved is of equal significance to me in my motivation to understand Arnold's capabilities and limitations, and I have noted its successes and failures in the Yes/No column of Appendix 2's spreadsheet. In this deciding of Yes/No, it should be noted that these judgments have been made by my eyes, deemed by me as Goethe describes in a "healthy state".[53] It is then assumed that all healthy eyes will be able to experience *Theory of Colour*'s results.

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[52]Autodesk Mudbox, base mesh: Man
[53] TOC, paragraph 45

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Extending Goethe's experiments into the digital realm is an act in merging the past with the present. My motivation for these recreations is to engage with Arnold's attributes as they foundationally exist, and to test their abilities by stripping back the range of choices in an exercise to test their fundamental features against practical real-world implements and scenarios. For Arnold, this exercise is a rigorous one, as Goethe's experiments were designed tirelessly by a man who yearned for comprehensive knowledge encompassing all of nature versus the limited abilities of a given renderer. It will put several of Arnold's attributes to the test, and ultimately, will inform me of Arnold's abilities and potential inabilities to generate the variety of optical phenomena experienced by Goethe. Parallels drawn and insights made will be brought back to the classroom, where my students may benefit greatly going forward in the making of their rendering decisions.

***

At the onset, Arnold's physically based rendering has an advantage. It has been intentionally designed to imitate the behaviours of natural light. Arnold's tools technically encompass all the needs for this recreation. Represented in Arnold's robust render package are extensive surface and light libraries that correspond to all phenomena as we see it in the world. They are presented in Arnold as such:
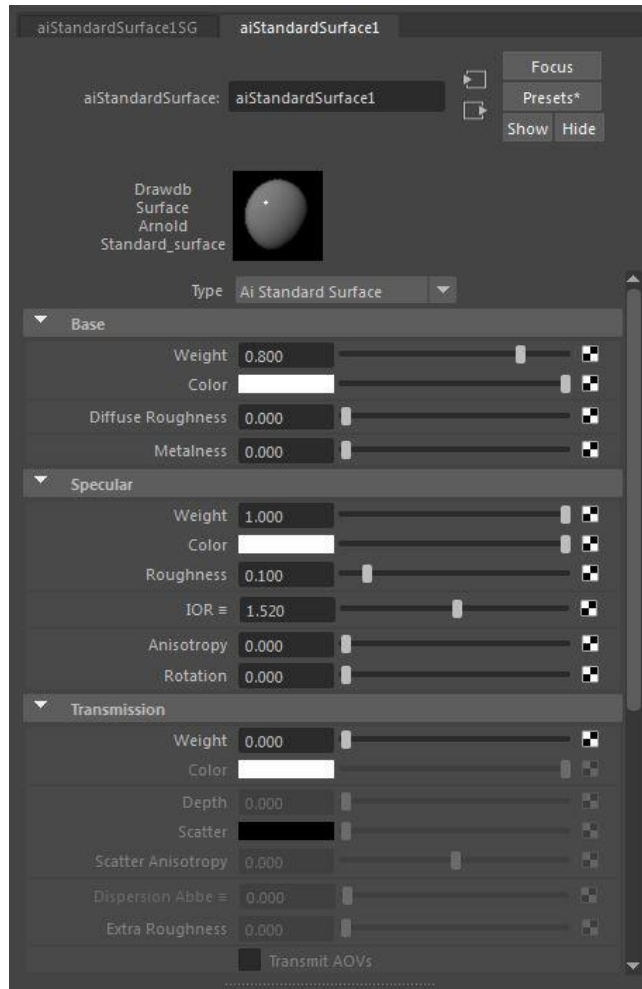
Fig. 12. Screen capture, *Arnold's Surface Properties window*, Autodesk Maya 2019
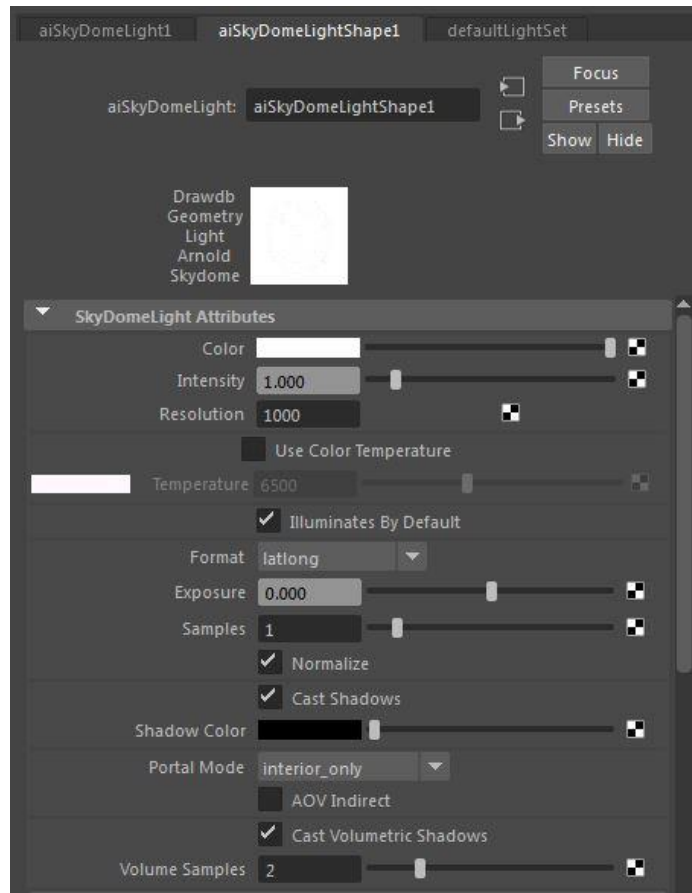
Fig. 13. Screen capture, *Arnold's aiSkyDomeLight Properties window*, Autodesk Maya 2019

The first image is of the attribute window for Arnold's Standard Surface Shader, known as

aiStandardSurface. As in nature, we see light only when it strikes something. Therefore,

surface attributes in Arnold contain light-related functionalities. Surfaces of 3D objects require

light to interact with them such that their shape and form can be discerned for the purposes of

animation and modeling. By and large, surface attributes are the most significant attributes to

adjust while rendering.

The second image is of the attribute window for Arnold's Dome Light; aiSkyDomeLight. In

accordance with the law of optics, light interacts with a surface in only four ways.[54] It can be absorbed (often causing a diffused appearance), reflected (causing a shiny appearance on a surface known as specularity), or be transmitted through an object – what we know as transparency. The fourth, emission, is when light is excited off the surface of an object; how we would describe the sun, or the flame of a candle. aiStandardSurface is the one all-encompassing surfacing tool offered by Arnold to generate these optical laws, and is the surfacing tool utilised the most in my study.

***

In Part I, Goethe introduces us to what he calls **Physiological Colours**. Physiological colours are produced by the eye as after-images: responses to an exposure of chromatic or white light stimulation. Goethe describes grey as taking on opposite roles: in a dark environment, grey represents light to the eye, and in a light environment, grey takes on the role of dark. Regarding colour stimulus, Goethe describes that the eye has a unique complimentary value that it produces as chromatic response. Goethe romantically encapsulates this, saying: "The eye creates freedom for itself by producing the opposite of that which is forced upon it, creating in this way a satisfying whole".[55] The use of candlelight as well as a phenomenon of sunlight is explored in Part I, and concepts of the colour wheel begin to present themselves as well. These concepts are more thoroughly revisited by other means in Part II. Arnold expresses these kinds of ideas as the interaction of light with surfaces, however, it is real-world qualities

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[54] Nelson, Ken. "Behavior of Light as a Wave." Ducksters, Technological Solutions, Inc. www.ducksters.com/science/physics/light_as_a_wave.php. Accessed August 2020
[55] TOC, paragraph 8

against which Arnold is being measured. All four ways that light interacts with surfaces are tested in Part I by Arnold, and are detailed below:

Experiments of particular interest conducted from Part I:

14_1) Coloured Objects

16_4) Coloured Objects

22_3) Coloured Shadows

25_1) Faint Lights

30_2) Subjective Halos

14_1) Coloured Objects and 16_4) Coloured Objects are experiments testing the eye's response in producing the opposite colour to that of which it is exposed. These experiments might not appear to be so much a test to Arnold since it is the eye which is creating the results, but for the eye to create these results from practical objects tests Arnold's ability to fulfill the experience digitally, in these experiments and all others. In this experiment, Arnold passes. Historically, as noted in the spreadsheet for 14_1 Coloured Objects, the bright-coloured silk stuff Goethe might have used for this experiment could have been coloured Prussian blue, which was widely synthesised and available in Germany from the mid-1700s.[56] Thus, the healthy eye, upon exposure to the blue on a moderately lighted white surface would respond with a yellow after-image as is satisfied in this experiment.

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[56] Stahl, G. E. (1731) "Experimenta, Observationes, Animadversiones". Numero, Chymicae et Physicae. Berlin. pp. 281-283, and TOC paragraph 577

Likewise, 16_4) Coloured Objects tests Arnold's digital abilities to capture the phenomenon, this time using coloured glasses. A grey-skied, relatively colourless photograph of Galway, Ireland taken by me in January 2020 is enlivened by being looked upon through blue and green panes of glass, colour-picked from Forest Glass (Waldglas) images of blue and green household glassware which were local and might have been accessible to Goethe in his time.[57] The image is yellowed with the removal of the blue glass, and is made slightly more pink with the removal of the green glass, as Goethe has written. Both panes of coloured glass utilise the transmission attribute in their aiStandardSurfaces at 0.75% capacity, to remain as true to their original glassware appearance, and to allow for equal exposure of the Galway image in satisfying the result of opposing colours created on it by the eye.

22_3) Coloured Shadows and 25_1) Faint Lights are experiments Goethe conducted using the main source of light for most dark conditions of his day, candlelight. For a candle to burn, the wick is ignited which melts and heats the candle's wax. The wax, in combination with oxygen in the air, ignites and forms a flame: an entity of combustion. As discussed, for a surface to be seen, light is required to interact with it. Therefore, the creation of a 3D flame for Arnold to interpret emission requires the flame to be a shape with a surface on which the emission attribute can be applied. Informing the emission setting's colour is the colour channel's attribute, which I have created from a ramp shader. The following images describe these chosen settings in how I constructed the candle:

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[57] Tait, H., 1991. Five Thousand Years of Glass. British Museum Press, London.
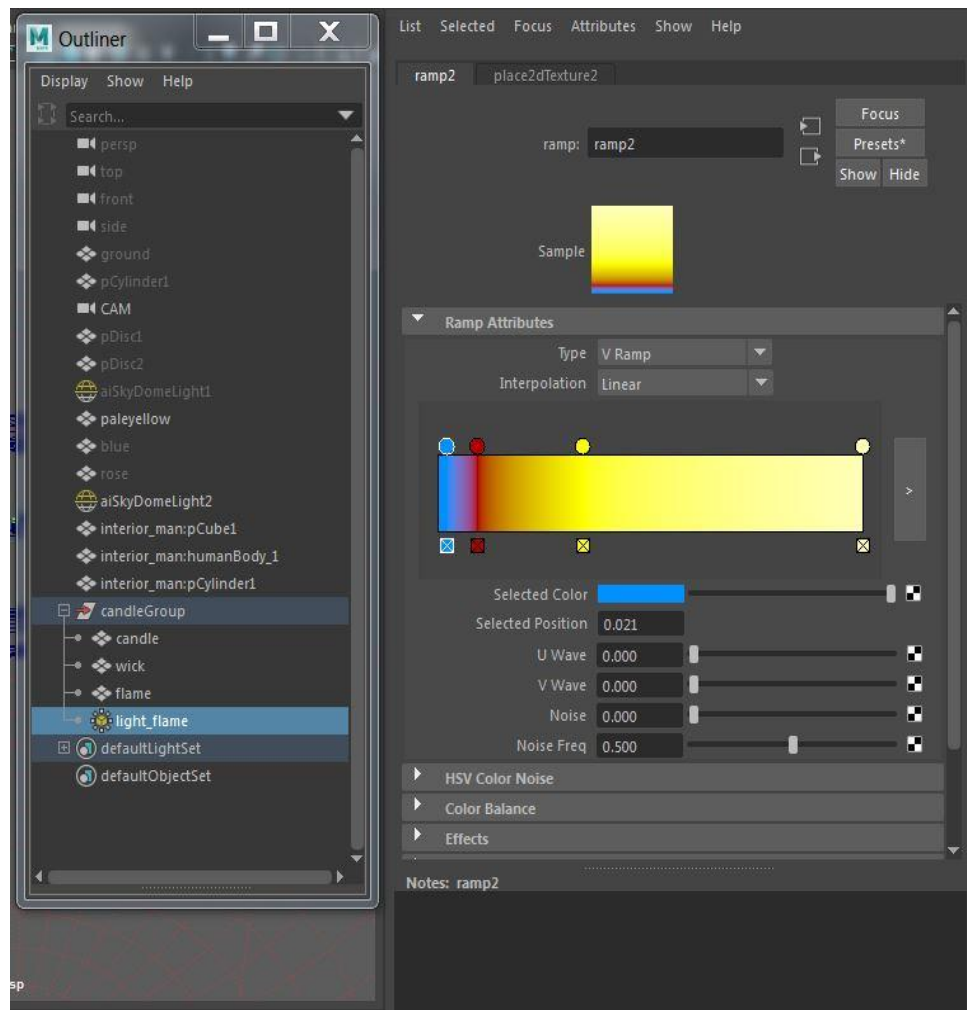
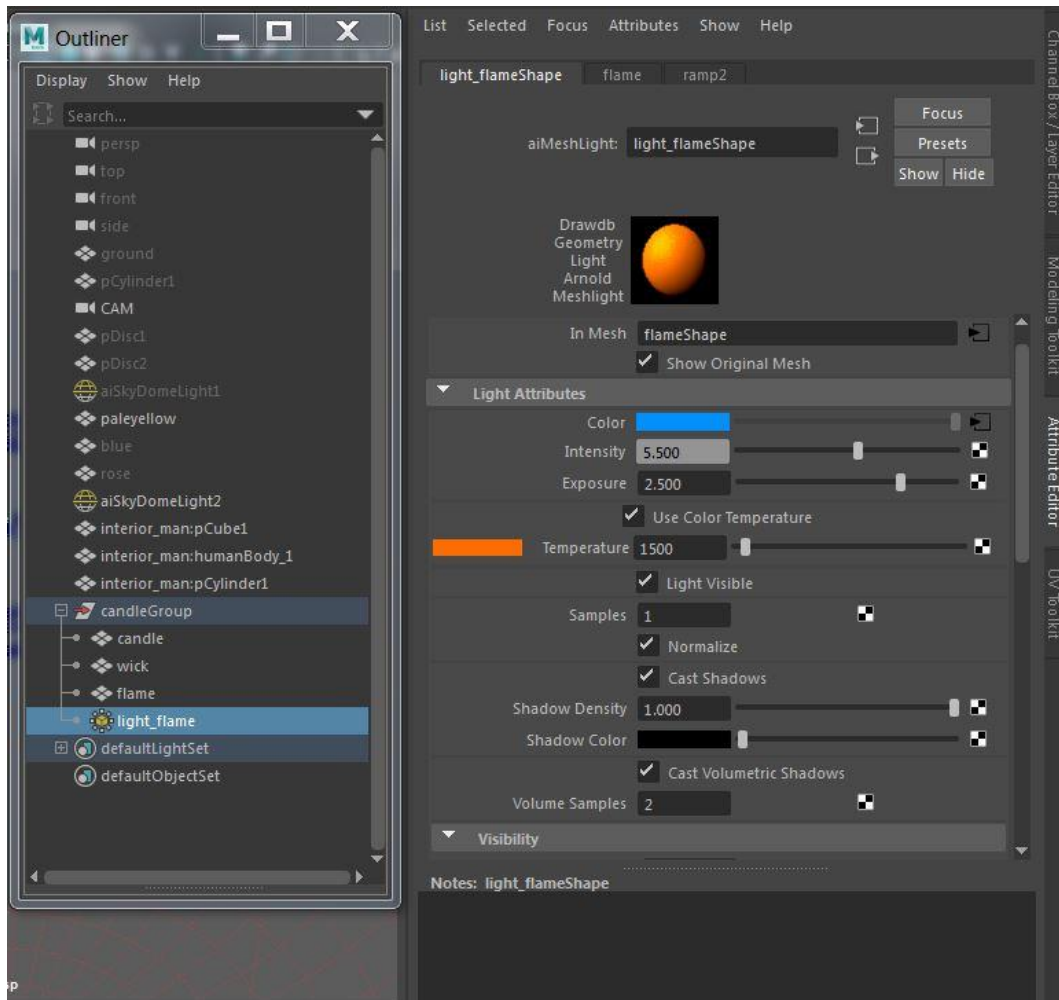Fig. 14. Screen capture, *Maya's ramp shader*, Autodesk Maya 2019

Fig. 15. Screen capture, *Arnold's MeshLight Properties window*, Autodesk Maya 2019

The first image illustrates the ramp shader I created, based from my observation of a lit wax

candle at night. This shader is then plugged into the colour channel of the light attributes of an

AiMeshLight; a light tool that, when assigned to any object, allows for that object to emit light.

As seen in the second image, Arnold's light attributes sophisticatedly consider the use of colour

temperature, which for a candle is 1500 Kelvin.[58] Important real-world features to take into

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[58] Segal, David. "What is Correlated Colour Temperature?". LEDSave, LEDSave.co.uk.
https://ledsave.co.uk/blog/what-is-correlated-colour-temperature. Accessed March 2020

consideration and enable in this menu are for the original mesh to be shown so that we can see the colour ramp, and for the flame to be able to cast a shadow. Arnold's ability to create natural-looking emitted light is ultimately put to the test through rendering all of these settings, and in 22_3) Coloured Shadows and 25_1) Faint Lights, we indeed see a yellowish light illuminating the scene and all objects therein, shadows of the candle and other objects, and in 23_1) Coloured Shadows, the candle's ability to reflect.

In 22_3) Coloured Shadows, there are two parts to the experiment. Not only are the colours of the candle-lit shadows put to the test; the digital candlelight must work in conjunction with Arnold's transmission attributes applied to the coloured glass to satisfy the experiment.[59] Placing a thin rod between the two candles indeed yields two shadows from the rod. By placing a coloured glass in front of one candle, dividing the scene, each of the candle's shadows and those of the rod take on separate, complemental colours of blue and yellow. This is impressive.

25_1) Faint Lights showcases the Arnold candle's capability in giving a yellowing effect to pale yellow, blue, and rose-coloured cards. This experiment unfolds by showing the darkened, candle-lit situation, followed by a medium-lit background with the same card as it appears in white light. As Goethe saw, under the influence of candlelight, the pale yellow appears as though it could be a white card, the blue card appears a navy-turquoise, and the rose-colour card appears orange. This experiment showcases the digital candle's unbiased ability to yellow differently coloured objects.

30_2) Subjective Halos concerns the phenomenon we see of the sun's halo reflected in water. Reflections by their definition are the yields of light's secondary bounce. In this experiment and

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[59] Tait, H., 1991. Five Thousand Years of Glass. British Museum Press, London.

throughout Part I, Goethe argues that looking directly at dazzling light is such an arresting action upon the eye that we are unable to see subtleties and other more elusive phenomena.[60] For this experiment, to behold these subtleties he directs the eye to the water's reflected image. For Arnold, this is an examination of both shader and light attributes, the first concerning aiStandardSurface's specularity applied to a plane representing placid water at 100%, and the second, the use of an intriguing light: AiPhysicalSky. This is a dome light based on reality. It is designed to imitate the appearance of the sky as the sun both illuminates the atmosphere and appears relative to the featured horizon line. Using a polar coordinate system, in its interaction with the fully specular plane, radiance and other cosmic attributes such as the sun's tint, size and scale, and turbidity of the environment are reflected. An important feature of this tool is the automatic reddening of the sky as the sun is animated closer to the horizon line. By using the tool's settings all at default state, for this experiment I animate the sun in two elevation positions: high and low on the horizon, since Goethe was not specific. The sun's reflected image is seen in both positions. AiPhysicalSky successfully emulates the effects of turbidity in our experience of the setting sun. This is an instance of *steigerung*, a phenomenon discussed in Part III. Specifically, at lower elevation, we see the sun's reflected halo exactly as Goethe saw it: "A halo… is found to be encircled towards its edge with a yellow border".[61] This yellow halo introduces a phenomenon explored in Part II of *Theory of Colours*: *boundary spectra*. For AiPhysicalSky to achieve this phenomenon is very interesting, especially since AiPhysicalSky presents in Arnold's light library with a disclaimer stating that it is an

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[60] "If we look on a white, strongly illumined surface, the eye is dazzled, and for a time is incapable of distinguishing objects moderately lighted." TOC, paragraph 7

[61] TOC, paragraph 94

experimental shader.[62] Based on the Hosek-Wilkie Sky Dome Appearance Project, AiPhysicalSky

appears to not have been further developed since the date of February 22, 2013, where an

update in the code for the Solar Radiance Function was added.[63] For such a light in a physically

based rendering package to not receive further attention, yet present disclaimed in the Arnold

library version after version as arguably the most physically based tool, in the field of computer

graphics where rendering research and development is of major focus, is fascinating to me in

my study. Validating patterns seen in Part II, for Goethe to have observed a yellow halo caused

him to question whether this experiment is subjective at all.[64] Thoughts on AiPhysicalSky as it

relates to this experiment, *boundary spectra*, and my rendered results from Parts II and III

culminate in the Conclusion of this paper as there are interesting implications.

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In Part II, **Physical Colours**, conditions where colours are created by colourless mediums and

materials are examined. In many of his experiments in Part II, Goethe implemented lenses and

prisms to obtain these colours, often revealing themselves as chromatic aberration, where the

lens is unable to focus all of the refracted light to the same point, causing a splay of banded

colours as the result. It was by these examinations of colour seen through lenses under

repetitive investigation where a law that must govern colour became most conceivable to

Goethe. A prism placed over a border of light and dark revealed rising patterns of blue and

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[62] Griggs, Lee. "Physical Sky". docs.arnoldrenderer.com. docs.arnoldrenderer.com/display/A5AFMUG/Physical+Sky. April 2020. Accessed May 2020

[63] Wilkie, Alexander, and Lukas Hosek. "Predicting Sky Dome Appearance on Earth-like Extrasolar Worlds". 29th Spring conference on Computer Graphics (SCCG 2013). Smolenice, Slovakia. May 2013. Accessed February 2020

[64] "We have already seen that a yellow border is apparent round the white space… This may be a kind of objective halo". TOC, paragraph 97

yellow in favour of the light edge, and red and violet in favour of the dark edge. Goethe wrote

extensively about borders and edges, which he called *boundary spectra*. Goethe distinguished

between them as the outer, broader border versus the narrower inner edge.[65]

Between these boundaries, at a certain tilt of the prism, would the balance of the rainbow be

revealed, thus revisiting concepts of the colour wheel, and again giving testament to the

possibility of colour's law. Represented in nature, at night's onset, the earth's atmosphere

reddens with the setting sun to the west, and to the east, we see earth's rising violet shadow.

Part II examines whether Arnold's tools and their attributes can produce the natural

phenomenon of coloured refraction. The first three of the four experiments of particular

interest were chosen to thoroughly test the possibility of this:

Experiments of particular interest conducted from Part II:

39_1) Conditions of the Appearance of Colour

41_1) Grey Objects Displaced by Refraction

42_2) Coloured Objects Displaced by Refraction

43_1) Catoptrical Colours

39_1) Conditions of the Appearance of Colour, 41_1) Grey Objects Displaced by Refraction, and

42_2) Coloured Objects Displaced by Refraction are experiments requiring the use of prisms to

reveal the phenomenon of *boundary spectra*. These three experiments are highlighted as of

particular interest to me due to fact that the same phenomenon is achieved by Goethe through

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[65] TOC, paragraph 212

unique combinations of tools, coloured and grey-scale plates, and black and white disks.

Rotating a thick convex lens over a small black disk atop a larger white disk, Goethe notes that by peering through the lens during its magnification of the disks creates at the boundary between black and white a band of the colours blue and yellow rising and falling from view (39_1) Conditions of the Appearance of Colour).

In same manner, by peering through a triangular rotating prism, Goethe notes that for various shades of grey placed next to each other, the boundary edges between the shades will react with the prism, creating a similar chromatic response (41_1) Grey Objects Displaced by Refraction).

Through the same triangular rotating prism, if the shades of grey were replaced with red and blue squares, Goethe notes "Similarly coloured edges and borders will appear above and below at the outlines of both. Red is proportionally much lighter on black than blue is. The colours of the edges will therefore appear stronger on the red than on the blue".[66]

To further explain *boundary spectra* as documented by Goethe in *Theory of Colours*, here are his own drawings illustrating two of these experiments discussed above:
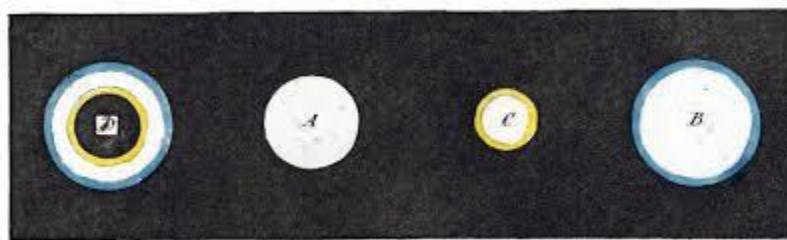

Fig. 16. Johann Goethe, *Theory of Colours Fig. 1.ii,* 1997

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[66] TOC, paragraph 262

For 39_1) Conditions of the Appearance of Colour, the blue and yellow *boundary spectra* in are

seen in figure D. A black disk atop a larger white disk, seen through a rotating convex lens

reveals blue at the boundary of black, and yellow at the boundary of white.
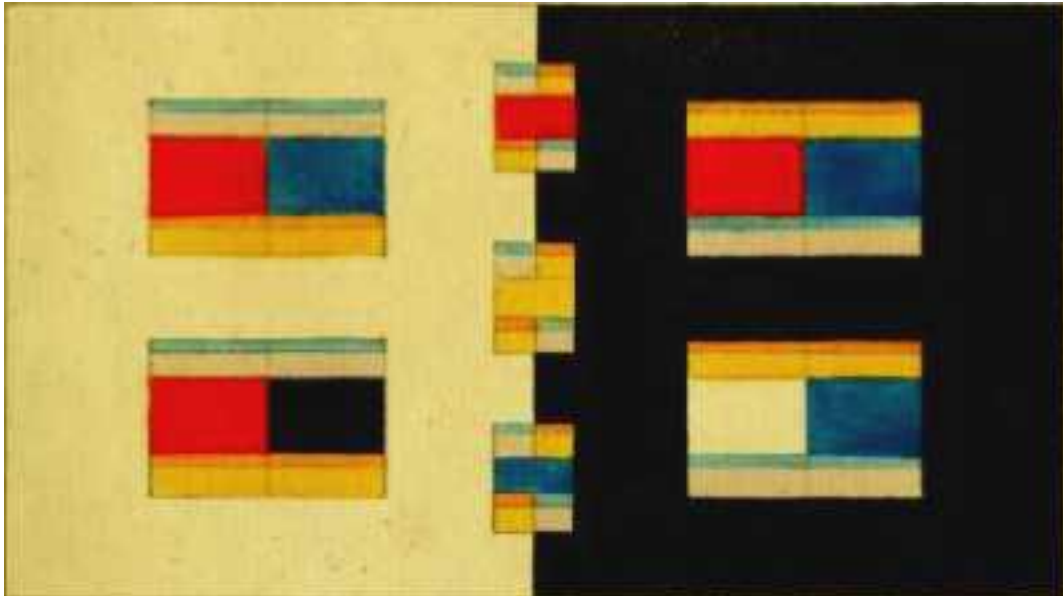

Fig. 17. Johann Goethe, *Theory of Colours Fig. 1.iv,* 1997

For 42_2) Coloured Objects Displaced by Refraction, at the intersection of the edges of red and

blue, are the boundary colours of yellow and blue to varying degrees of strength, as discussed

by Goethe.

Lenses and prisms are pieces of clear glass. In the action of looking through them, what I see

puts Arnold's transmission and refraction attributes to the test. In their construction, polygonal

shapes according to Goethe's description were modeled, and were assigned transmission

weight values of 1: the maximum. When transmission is at its maximum value, the Base, or

Arnold's absorption parameter is disabled since at this state these laws are in opposition

because a fully transparent item does not absorb light. Following Arnold's online recipe for glass attribute settings, specularity and index of refraction values were adjusted to that of glass (full-strength value of 1, and 1.5 IOR).[67] The curious thing about clear glass is that it is both clear and yet visible to us. We can discern the shapes of lenses and prisms simply by how the lenses and prisms are distorting the appearance of everything around them, including what we look through them to see.

This is where Arnold partially falls short. In my experiments, the disks, planes, and red and blue squares indeed have their shapes distorted by the lens and prisms as they rotate over them, but what causes *boundary spectra* is a secondary refraction occurring simultaneously inside the prism – everything within the scene is refracted; light and dark. In the real world, as we can see today by repeating these experiments with our own lenses and prisms, Goethe would have had lots of light around him. Unless in complete darkness, light bounces off nearly everything, directly and most often diffusedly: illuminating the things we see even when the sun is not directly shining on us or them. That diffused, indirect light also makes its way into the lenses and prisms, and affords us the secondary visual result of *boundary spectra*. The reason why Arnold does not simultaneously compute *boundary spectra* is because of how it is built.

Arnold's method of rendering, path tracing, allows for light in the 3D scene to behave in true-to-life manner. Literally, light's path is traced from its source and is calculated throughout the

[67] Griggs, Lee. "Shading Glass and Liquid". docs.arnoldrenderer.com.
docs.arnoldrenderer.com/display/A5AFHUG/Shading+Glass+and+Liquid. March 2019. Accessed March 2020

scene as it bounces from object to object, behaving as needed according to assigned shaders, and casting secondary lighting onto items in the scene. Upon arriving at the camera, we see these calculated results carried along each path as realistic in appearance, because this is what photons of light do in reality before they hit our eyes.

The way that Arnold has been built to do this is unidirectionally, meaning, once a surface with a certain attribute is struck by light along a path, there can be only one behaviour, or one calculation picked up to be carried along that path. In Arnold's attempt at 39_1) Conditions of the Appearance of Colour, 41_1) Grey Objects Displaced by Refraction, and 42_2) Coloured Objects Displaced by Refraction, the refraction of the disks, planes, and squares is one act of refraction within the lens and prisms, and the *boundary spectra* would be a simultaneous, secondary behaviour. This discrepancy between real-world phenomena and renderable design due to narrative choices is an interesting reflection showing the limitations of our current models and tools in the realm of representation. From Arnold's website,

"Sophisticated bidirectional methods are generally more robust to varying lighting configurations than unidirectional path tracing, but in the vast majority of production scenes, they result in slower renders and also complicate the computation of ray differentials with respect to the camera".[68]

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[68] Georgiev, Iliyan et al. "Arnold: A Brute-Force Production Path Tracer". ACM Transactions on Graphics Vol. 37 No. 3. https://dl.acm.org/doi/10.1145/3182160. August 2018, Accessed August 2020

A bidirectional calculation would mean that once a surface with a certain attribute is struck by light along a path, attributes of that surface would be plurally discerned, and a simultaneous, secondary path would be formed, and carry on in like manner throughout the scene before arriving at the camera. Since Arnold is Maya's inherent renderer, and is used in studio pipelines all over the world, unidirectional path tracing has been decided by the makers of Arnold to be the path tracing style of choice because of speed. Simply, we cannot render *boundary spectra* with Arnold.

We can, however, achieve the look with external help. Prismatic shader algorithms are available for download to be plugged-in to most render engines, and rely on how the scene is modeled. Models working in hierarchy with bidirectional rendering in mind are called nested dielectrics.[69] This system, introduced in 2002 by Schmidt and Budge, is still widely the system used today. The concept is that one refractive behaviour exists, or is nested, as secondary to a primary refractive behaviour. The render of nested dielectrics may appear faithful to reality, but it is a calculation based entirely on the allocation of items within a scene.

What if there was a way that Arnold could achieve *boundary spectra* using an intuitive, physically based approach, and continue to trace paths unidirectionally? Considering real lenses and prisms are solid pieces of clear glass, for a ray of light to enter, travel through, and leave the prism, the ray is passing through different states of matter: gas, solid, and back to gas.

[69] Schmidt, Charles; Brian Budge. "Simple Nested Dielectrics in Ray Traced Images". *Journal of Graphics Tools, 7:2, 1-8*. March 2002. Published online April 2012. Accessed August 2020

When a different medium is encountered by the ray of light, refraction, or the redirection of light, is the ray's natural response. Glass is denser than air, and so when a ray of light enters the prism, it slows down. The law of optics that governs to what angle rays of light will refract upon entry of media is known as Snell's Law. Air and glass have established angles of refraction, according to their densities. Implicit in its expression, Snell's Law integrates turbidity in the falloff. Below is an image illustrating the passage of a ray of light from air through glass, and back to air. Note that the angle of the incident ray is the same as the angle of the emergent ray, as per Snell's Law.
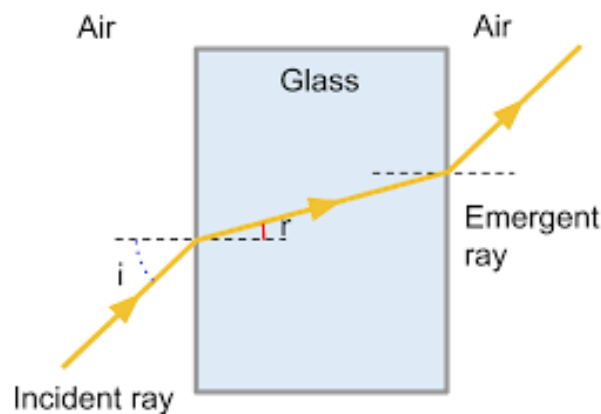

Fig. 18. Nick England, *AQA A Level Physics, Fig. 83*, 2015

In 3D, light passing through polygonal shapes does not work this way at all. 3D objects exist essentially as meshes, which can represent only surface qualities and behaviours. Applying any surface attribute to a polygon, from Arnold's aiStandardSurface to those for nested dielectrics, affects only the polygon's mesh, and not its interior volume. Index of refraction is an attribute of aiStandardSurface's specularity, and not its transmission.

43_1) Catoptrical Colours is an examination of the attributes associated with roughness.

Roughness, or the scruffiness of an appearance, acts as crude refraction; a forced redirection of

light from an object's surface. The enhancement of the roughness attribute conversely tests

the efficiency of the specular attribute. Goethe explores roughness by scuffing up a mirror and

placing it flat on the ground so that it reflects the sun. He also pulls apart a metal spring

enough for it to crack, and lets it bounce back together, observing how the exposed silvery

indentations behave in the sun. For this experiment, using the AiPhysicalSky with default sun

settings at the apex, or "noon", I combined Goethe's doings, and, since the items of his

experiments are metallic, over 100 frames I have animated the specular roughness of the two

items, from 0 to 1 (the attribute at 100%). Goethe saw that by scuffing up the surfaces from

their intact state, reflection was skewed enough that the indentations made were reflecting

upon themselves, creating an iridescent, diffused appearance. This experiment tests the

breadth of Arnold's specular function, which yields these same results. At the full roughness

value, the surfaces are exactly as they should be: they are so rough that they become dull, and

therefore, the whole scene appears darker. The light that once was easily reflected is now

maximally obscured. From about 30% to 80% roughness, the spring appears to sparkle with the

sun's reflection as Goethe saw, and at this same point, the mirror demonstrates the halo

phenomenon, seen in 30_2) Subjective Halos. Even on a scuffed surface, the halo continues to

validate boundary patterns seen in Parts I and II.

Boundary spectra by their name are concerned with limits, and present themselves as potential

laws of light, as seen in 30_2) Subjective Halos and 43_1) Catoptrical Colours. For refraction to

occur in a prism, a boundary is necessary. In the Conclusion of this paper, I argue that 3D

boundaries are missing from a more robust Arnold, and I propose an idea alternative to nested

dielectrics based on my intuition that this same boundary model is what affords AiPhysicalSky's

ability to represent natural phenomena. Finite boundary concepts are further validated in the

examination of Part III, *steigerung*.

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In Part III, **Chemical Colours**, light's ability to create colour with coloured mediums is examined.

Most notable in this Part is the phenomenon of *steigerung*: the augmentation of colour.

Steigerung further validates the laws of *boundary spectra* as experienced when yellow

materials redden in colour as observed through thickening or turbid media.

Experiment of particular interest conducted from Part III:

48_1) Augmentation of Colour

48_1) Augmentation of Colour is an experiment which revealed a phenomenon akin to what

Goethe saw in 30_2) Subjective Halos, and the *boundary spectra* in 39_1) Conditions of the

Appearance of Colour. On the subject of augmentation, Goethe wrote:

"The augmentation of colour exhibits itself as a condensation, a fulness, a darkening of the hue.

By increasing the degree of opacity in the medium, we can deepen a bright object from the

lightest yellow to the intensest ruby-red. This is one of the most important appearances

connected with the doctrine of colours, for we here manifestly find that a difference of quantity

produces a corresponding qualified impression on our senses".[70]

In Goethe's time, optical phenomena such as this were largely unexplained. Yet to come along

with significant contributions to the field were Hermann Helmholtz (b. 1821) and August Beer

(b. 1825). [71] [72] Even though Goethe believed that mathematical abstraction was a hindrance to

the understanding of things, his observation in this experiment is now a practical marvel of

physics known as Beer's Law: a law which describes the attenuation, or gradation of light in a

material through which the light is traveling.[73] The denser the material, the greater the loss of

light intensity within that material, and thus an appearance of darkening.

In my online compendium, the animation of 48_1) Augmentation of Colour consists of a still

frame extended for fifteen seconds to show the white cup and its yellow contents, with a blue

stripe added to the interior surface of the cup in order to define its shape from lip to bottom.

The settled yellow liquid seen in the still frame was created to fall into the cup as realistically as

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[70] TOC, paragraph 212

[71] Hermann von Helmholtz was a scientist who made fundamental contributions to optics and mathematics. Helmholtz validated mathematically many philosophical assumptions on which much 19th-century science was based. His greatest work is The Handbook of Physiological Optics (1867). To read more on Helmholtz: Masters, B.R. "Hermann von Helmholtz: A 19th Century Renaissance Man." Optics and Photonics News. March 2010. pp. 34-39. Accessed November 2019

[72] August Beer is known for his eponymous law which describes the attenuation of light as it travels through transparent materials. Beer's Law can be further explored here: Onorato, P. "The Beer Lambert Law Measurement Made Easy." Physics Education, Volume 53, Number 3. April 2018. Accessed November 2019. iopscience.iop.org/article/10.1088/1361-6552/aab441

[73] Goethe speaks about "prejudiced mathematicians" who are "prevented by occupation" from being enlightened from unbridled observation, not only with relation to colour but all phenomena. He has also said: "Mathematicians are like Frenchmen; whatever you say to them, they translate it into their own language, and forthwith it means something entirely different" TOC, paragraphs 725-728

Maya and Arnold's tools could provide. Below is a Playblast animation from the scene's

perspective view, showing the location of the camera, and the application of dynamic particles

assigned to behave as liquid, filling the cup seen in the final render. This animation is also part

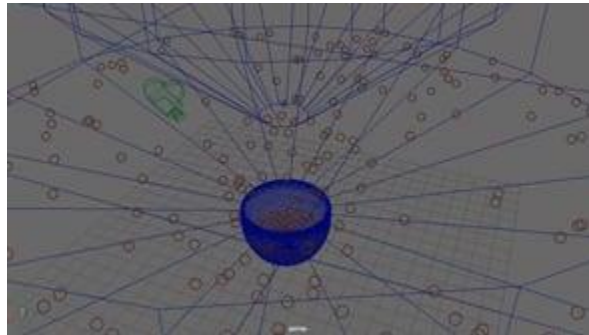of the compendium, and can be viewed here: vimeo.com/451280364

Fig. 19. *Playblast animation*, Autodesk Maya, created by the author, 2020

It is important to show this crude animation as part of my process, however it is the last

rendered frame of the settled liquid which reveals the success of the experiment. As seen in

the online animation, the liquid particles were assigned a yellow transmission colour as part of

Arnold's tools which include Beer's Law in their functionality, and the cup was assigned as a

passive rigid body; Maya's method of creating barriers from polygonal mesh. [74],[75]

Like what Goethe saw around the sun in 30_2) Subjective Halos, and the *boundary spectra* he

described in 39_1) Conditions of the Appearance of Colour, this experiment is one which relies

on a boundary in order to witness colour intensification – an effect Goethe called *steigerung*.

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[74] As per the Autodesk webpage on Beer's Law as it integrates with Arnold: The longer light travels inside a mesh, the more it is affected by the *transmission color*. Therefore, green glass gets a deeper green as rays travel through thicker parts. The effect is exponential and computed with Beer's Law. It is recommended to use light, subtle color values. More here: Griggs, Lee. "Shading Glass and Liquid". *docs.arnoldrenderer.com*. March 2019. Accessed March 2020

[75] Ford, Chris. "Rigid bodies". Autodesk Knowledge Network. knowledge.autodesk.com. September 2014. Accessed August 2019

Although unable to produce *boundary spectra* in the prism experiments, Arnold considers Beer's Law in its Transmission shader properties. Further, barriers can be assigned to mesh as part of Maya's particle library for the use of dynamics. The combination of these two 3D tools however still does not cause the yellow liquid particles to intensify their colour. This is due to the fact that many liquid particles working together are not programmed to satisfy a collective volume, even when they are contained collectively by an allocated boundary. The Beer's Law aspect of Arnold's Transmission shader is therefore abstract, and is presented like its other tools as a slider for the user to dial up or down the intensification of the colour, causing Beer's Law to activate off dialed calculation and not from volumetric objects within the scene.

This points again to the polygon's limitations as seen in the prismatic experiments 39_1) Conditions of the Appearance of Colour, 41_1) Grey Objects Displaced by Refraction, and 42_2) Coloured Objects Displaced by Refraction, where without volume, it is difficult to account for changes in refraction due to density, therefore neither Snell's Law nor Beer's Law are accurately attainable.

Because of the limitations of mesh-based models, a strategy based on Goethe's distinction between borders and edges may be useful in providing indications for rendering: "The colour which is outside, or foremost, in the apparent change of an object by refraction, is always the broader, and we will henceforth call this a border: the colour that remains next the outline is the narrower, and we will call an edge".[76]

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[76] TOC, paragraph 212

Conclusion

Is it possible to create a 3D-bounded space to allow for the phenomena of *boundary spectra* and turbidity? Goethe's observation of boundary colours, and the increasing of colours (*steigerung*), is explained by how sunset increases to yellow-red because the sun is traversing turbidity in order to reach our eyes. Looking through a prism at the boundary of black and white yields the blue and red colours we see in the sunset; the colours Goethe calls primordial.[77] This effect is also seen in a cup of mildly coloured tea: the surface of the tea is pale but at its boundary at the bottom of the cup it increases to yellow tending to red, just as the blue of the distant mountains.[78] In extending Goethe's experiments with Arnold have I discovered specifically where Arnold falls short in the rendering of light with intervening turbidity.

Given the shortcomings of AiPhysicalSky, we now have a specification against which improvements can be made. Goethe's catalog of human perceptions provides the acid test against which Arnold's abilities can be measured. This qualifies the promise of the new crop of real-world renderers, and how well they deliver on those capabilities.

With this paper, a basic test suite has been developed. This suite could be expanded to include a basic minimal definition. Other renderers can be tested against this specification, and their differences and abilities qualified. If I made the first steps in forming this specification, the task

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[77] "We call these primordial phenomena because nothing appreciable by the senses lies beyond it, on the contrary, they are perfectly fit to be considered as a fixed point to which we first ascended, step by step, and from which we may, in like manner, descend to the commonest case of every-day experience". TOC, paragraph 175
[78] TOC, paragraph 156

of scientifically informing rendering decisions with real world sensibilities will have been achieved.

Goethe wanted consistent reasons for the use of colour that were not arbitrary, and he was motivated to find these rules. The motivation which brought him to his endeavour has been realised through my study in a new medium.

***

As fascinated as I am about the advancements of rendering, evolving digital tools, and 3D material properties and their interactions, am I also continuously struck by the wondrous behaviour of light in the natural world around me. The interaction of sunlight and mist in their manifestation of a rainbow, the hot glow of a sunset: light is a constantly changing phenomenon as we perceive it.

We cannot throw away our continuous experience of colour in the real world. When we make mathematical models, we are no longer dealing with reality, we are dealing with the model. Then, how does the model relate to reality? We need compositing, AOVs, specially placed lights, fog, z-depth, and the tweaking of attributes to create a look that we take for granted. These are the things we have to do because we don't have real-world rendering. But, do we even want it? I argue that we must know the rules to break them, so, my hope for my students is to impart a knowledge of the real world so that they can be informed in their choices in their

creation of surreal worlds. If we wanted a real image, we would have photographs instead of paintings.

At the time of the writing of this paper, Pixar is announcing the release of its new "Stylized Looks" for Renderman™.[79] These "Stylised Looks" automate much of the technical aspect required to apply the demands of the audience – extending the stylization used in *The Hay Wain* by John Constable in 1821. A perceptual renderer based on Goethe's observations would create realistic images onto which stylistic variations can be applied, like filters to a photograph, delineating the real from the surreal. We want realistic renders so we can create a better surreal experience, and the offerings that create that experience keep growing.

Says Goethe of *Theory of Colours*:

"A dread of, nay, a decided aversion for all theoretical views respecting colour and everything belonging to it, has been hitherto found to exist among painters; a prejudice for which, after all, they were not to be blamed; for what has been hitherto called theory was groundless, vacillating, and akin to empiricism. We hope that our labours may tend to diminish this prejudice, and stimulate the artist practically to prove and embody the principles that have been explained".[80]

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[79] "Stylised Looks coming to Pixar's Renderman™ in version 24". Pixar advertisement released August 27, 2020
[80] TOC, paragraph 900

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Appendix I

Part I is chaptered as such:

<u>Effects of Light and Darkness on the Eye</u> (entries 1-14) **– Explanation only, no experiments described**

<u>Effects of Black and White Objects on the Eye</u> (entries 15-34) **– 7 experiments:**

1) Let a white disk be placed on a black ground, and a black disk be placed on a white ground, both being exactly similar in size; let them be seen together at some distance, and we shall pronounce the last to be about a fifth part smaller than the other. If the black circle be made larger by so much, they will appear equal.

2) Lights seen behind an edge make an apparent notch in it. A ruler, behind which the flame of a light just appears, seems to us indented.

3) The rising or setting of the sun appears to make a notch in the horizon.

4) If… we look intently at the bars of a window relieved against the …sky, and then shut our eyes or look towards a totally dark place, we shall see a dark cross on a light ground before us for some time.

5) If we shut the eyes immediately after looking at the sun we shall be surprised to find …the image it leaves appears.

6) If, while the image of the window-bars before-mentioned lasts, we look upon a light grey surface, the cross will then appear light and the panes dark.

7) If we look at a black disc on a light grey surface, we shall presently, by changing the direction of the eyes in the slightest degree, see a bright halo floating round the dark circle.

<u>Grey Surfaces and Objects</u> (entries 35-38) **– 3 experiments:**

1) Let a black object be held before a grey surface, and let the spectator, after looking steadfastly, keep his eyes unmoved while it is taken away: the space it occupied appears much lighter.

2) Let a white object be held up in the same manner: on taking it away the space it occupied will appear much darker than the rest of the surface. Let the spectator in both cases turn his eyes this way and that on the surface, the visionary images will move in like manner.

3) A grey object on a black ground appears much brighter than the same object on a white ground.

<u>Dazzling Colourless Objects</u> (entries 39-46) **– 3 experiments:**

1) Let a room be made as dark as possible; let there be a circular opening in the window-shutter about three inches in diameter, which may be closed or not at pleasure. The sun being suffered to shine through this on a white surface, let the spectator from some little distance fix his eyes on the bright circle thus admitted. The hole being closed, let him look towards the darkest part of the room; a circular image will now be seen to float before him. >The middle of this circle will appear bright, colourless, or somewhat yellow, but the border will at the same moment appear red. After a time this red, increasing towards the centre, covers the whole circle, and at last the bright central point. No sooner, however, is the whole circle red than the edge begins to be blue, and the blue gradually encroaches inwards on the red. When the whole is blue the edge becomes dark and colourless. This darker edge again slowly encroaches on the blue till the whole circle appears colourless. The image then becomes gradually fainter, and at the same time diminishes in size.

2) If we receive the impression of the bright circle as before, and then look on a light grey surface in a moderately lighted room, an image again floats before us; but in this instance a dark one: by degrees it is encircled by a green border that gradually spreads inwards over the whole circle, as the red did in the former instance. As soon as this has taken place a dingy yellow appears, and, filling the space as the blue did before, is finally lost in a negative shade.

3) These two experiments may be combined by placing a black and a white plane surface next each other in a moderately lighted room, and then looking alternately on one and the other as long as the impression of the light circle lasts: the spectator will then perceive at first a red and green image alternately, and afterwards the other changes. After a little practice the two opposite colours may be perceived at once, by causing the floating image to fall on the junction of the two planes. This can be more conveniently done if the planes are at some distance, for the spectrum then appears larger.

<u>Coloured Objects</u> (entries 47-61) **– 7 experiments:**

1) Let a small piece of bright-coloured paper or silk stuff be held before a moderately lighted white surface; let the observer look steadfastly on the small coloured object, and let it be taken away after a time while his eyes remain unmoved; the spectrum of another colour will then be visible on the while plane. The coloured paper may be also left in its place while the eye is directed to another part of the white plane; the same spectrum will be visible there too, for it arises from an image which now belongs to the eye.

2) I had entered an inn towards evening, and, as a well-favoured girl, with a brilliantly fair complexion, black hair, and a scarlet bodice, came into the room, I looked attentively at her as she stood before me at some distance in half shadow. As she presently afterwards turned

away, I saw on the white wall, which was now before me, a black face surrounded with a bright light, while the dress of the perfectly distinct figure appeared of a beautiful sea-green.

3) Those who wish to take the most effectual means for observing the appearance in nature – suppose in a garden – should fix the eyes on the bright flowers selected for the purpose, and, immediately after, look on the gravel path. This will be seen studded with spots of the opposite colour. The experiment is practicable on a cloudy day, and even in the brightest sunshine, for the sun-light, by enhancing the brilliancy of the flower, renders it fit to produce the compensatory colour sufficiently distinct to be perceptible even in a bright light. Thus, peonies produce beautiful green, marigolds vivid blue spectra.

4) …so the same effect takes place when the whole retina is impressed with a single colour. We may convince ourselves of this by means of coloured glasses. If we look long through a blue pane of glass, everything will afterwards appear in sunshine to the naked eye, even if the sky is grey and the scene colourless. In like manner, in taking off green spectacles, we see all objects in a red light.

5) To pursue a former experiment, if we look on a yellow piece of paper placed on a white surface, the remaining part of the organ has already a tendency to produce a purple hue on the colourless surface: in this case the small portion of yellow is not powerful enough to produce this appearance distinctly, but, if a white paper is placed on a yellow wall, we shall see the white tinged with a purple hue.

6) …yet red and green are particularly recommended for it, because these colours seem powerfully to evoke each other.

7) If we place a piece of paper of a bright orange colour on the white surface, we shall, after looking intently at it, scarcely perceive the compensatory colour on the rest of the surface: but when we take the orange paper away, and when the blue spectrum appears in its place, immediately as this spectrum becomes fully apparent, the rest of the surface will be overspread, as if by a flash, with a reddish-yellow light, thus exhibiting to the spectator in a lively manner the productive energy of the organ, in constant conformity with the same law.

Coloured Shadows (entries 62-80) – **7 experiments:**

1) A shadow cast by the sun, in its full brightness, on a white surface, gives us no impression of colour; it appears black or, if a contrary light (here assumed to differ only in degree) can act upon it, it is only weaker, half-lighted, grey.

2) Let a short, lighted candle be placed at twilight on a sheet of white paper. Between it and the declining daylight let a pencil be placed upright, so that its shadow thrown by the candle may be lighted, but not overcome, by the weak daylight: the shadow will appear of the most beautiful blue.

3) Place two candles at night opposite each other on a white surface; hold a thin rod between them upright, so that two shadows be cast by it; take a coloured glass and hold it before one of the lights, so that the white paper appear coloured; at the same moment the shadow cast by the coloured light and slightly illuminated by the colourless one will exhibit the complemental blue.

4) Select the moment in twilight when the light of the sky is still powerful enough to cast a shadow which cannot be entirely effaced by the light of a candle. The candle may be so placed that a double shadow shall be visible, one from the candle towards the daylight, and another from the daylight towards the candle. If the former is blue the latter will appear orange-yellow: this orange-yellow is in fact, however, only the yellow-red light of the candle diffused over the whole paper, and which becomes visible in shadow.

5) A white surface being placed opposite the full moon, and the candle being placed a little on one side at a due distance, an opaque body is held before the white plane. A double shadow will then be seen: that cast by the moon and illuminated by the candle-light will be a powerful red-yellow; and contrariwise, that cast by the candle and illuminated by the moon will appear of the most beautiful blue. The shadow, composed of the union of the two shadows, where they cross each other, is black. The yellow shadow cannot perhaps be exhibited in a more striking manner. The immediate vicinity of the blue and the interposing black shadow make the appearance the more agreeable. It will even be found, if the eye dwells long on these colours, that they mutually evoke and enhance each other, the increasing red in the one still producing its contrast, viz. a kind of sea-green.

6) Let a white paper blind be fastened inside the window on a winter evening' in this blind let there be an opening, through which the snow of some neighbouring roof can be seen. Towards dusk let a candle be brought into the room; the snow seen through the opening will then appear perfectly blue because the paper is tinged with warm yellow by the candle-light. The snow seen through the aperture is here equivalent to a shadow illuminated by a contrary light, and may also represent a grey disk on a coloured surface.

7) If we take a piece of green glass of some thickness, and hold it so that the window bars be reflected in it, they will appear double owing to the thickness of the glass. The image which is reflected from the under surface of the glass will be green; the image which is reflected from the upper surface, and which should be colourless, will appear red.

Faint Lights (entries 81-88) **– 4 experiments:**

1) Candle-light at night acts as yellow when seen near; we can perceive this by the effect it produces on other colours. At night a pale yellow is hardly to be distinguished from white; blue approaches to green, and rose-colour to orange.

2) Candle-light at twilight acts powerfully as a yellow light: this is best proved by the purple blue shadows which, under these circumstances, are evoked by the eye

3) …hence candle-light by day appears reddish, thus resembling, in its relation to fuller light, the spectrum of a dazzling object; nay, if at night we look long and intently on the flame of a light, it appears to increase in redness.

4) If at night we place a light near a white or greyish wall so that the surface be illuminated from this central point to some extent, we find, on observing the spreading light at some distance, that the boundary of the illuminated surface appears to be surrounded with a pale yellow circle, which on the outside tends to red-yellow. We thus observe that when light direct or reflected does not act in its full force, it gives an impression of yellow, or reddish, and lastly even of red. Here we find the transition to halos which we are accustomed to see in some mode or other round luminous points.

Subjective Halos (entries 89-100) **– 3 experiments:**

1) …in a dark room, if we look towards a moderately large opening in the window-shutter, …the bright image is surrounded by a circular misty light. I saw such a halo bounded by a yellow and yellow-red circle on opening my eyes at dawn, on an occasion when I passed several nights in a bed-carriage.

2) A light must shine moderately, not dazzle, in order to produce the impression of a halo in the eye; at all events the halos of dazzling lights cannot be observed. We see a splendour of this kind round the image of the sun reflected from the surface of water.

3) Halos may, however, appear extremely small and numerous when the impinging image is minute, yet powerful, in its effect. The experiment is best made with a piece of gold-leaf placed on the ground and illumined by the sun. In these cases the halos appear in variegated rays.

Pathological Colours (entries 101-135) **– Explanation only, no experiments described**

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Part II
Part II is chaptered as such:

To know:
Objective phenomena vs Subjective phenomena: Objective is based on facts or what is revealed. Subjective is based on personal preferences. "The world divides itself into two parts,

and the human being as subject, stands opposed to the object. Thus the practical man exhausts himself in the accumulation of facts, the thinker in speculation; each being called upon to sustain a conflict which admits of no peace and no decision" p. 75 It is our intention to separate objective from subjective appearances.

"The eye is not considered to be acting alone; nor is the light ever to be considered in immediate relation with the eye: but we direct our attention especially to the various effects produced by mediums, those mediums being themselves colourless"

Catoptrical: when light flashes back from the surface of a medium – closely connected to physiological
Paroptical: when light passes by the edge of a medium – distinct and independent
Dioptrical: when light passes through an actual transparent body – strictly physical, objective result. A colourless medium is necessary to produce these colours.
Epoptical: when the phenomena of colours exhibit themselves on colourless surfaces – transition to chemical colours

Dioptrical Colours
Dioptrical Colours of the First Class (entries 145-177) **– 12 experiments:**

imperfectly transparent yet light-transmitting mediums. Space is assumed as empty and therefore of absolute transparency. Semi-transparent mediums are accumulated forms of transparent mediums: pure, light-transmitting, semi-transparent. The extreme degree of accumulation is white. The opposite of white is transparent.
The sun is the highest degree of light. White, dazzling.
Introducing thickening mediums to light/dark scenarios reveal remarkable phenomena

1) The sun…is dazzling and colourless: so the light of the fixed stars is for the most part colourless. This light, however, seen through a medium but very slightly thickened, appears to us yellow. If the density of such a medium be increased, or if its volume become greater, we shall see the light gradually assume a yellow-red hue, which at last deepens to a ruby-colour.
2) if on the other hand darkness is seen through a semi-transparent medium, which is itself illumined by a light striking on it, a blue colour appears: this becomes lighter and paler as the density of the medium is increased, but on the contrary appears darker and deeper the more transparent the medium becomes: in the least degree of dimness short of absolute transparence, always supposing a perfectly colourless medium, this deep blue approaches the most beautiful violet.
3) the sun seen through a certain degree of vapour appears with a yellow disk; the centre is often dazzlingly yellow when the edges are already red. The orb seen through a thick yellow mist appears ruby-red (as was the case in 1794, even in the north); the same appearance is still more decided, owing to the state of the atmosphere, when the scirocco prevails in southern climates: the clouds generally surrounding the sun in the latter case are of the same colour, which is reflected again on all objects.

4) the red hues of morning and evening are owing to the same cause. The sun is announced by a red light, in shining through a greater mass of vapours. The higher he rises, the yellower and brighter the light becomes.

5) If the darkness of infinite space is seen through atmospheric vapours illumined by the day-light, the blue colour appears. On high mountains the sky appears by day intensely blue, owing to the few thin vapours that float before the endless dark space: as soon as we descend in the valleys, the blue becomes lighter; till at last, in certain regions, and in consequence of increasing vapours, it altogether changes to a very pale blue.

6) so we find the shadowed parts of nearer objects are blue when the air is charged with thin vapours.

7) the snow-mountains, on the other hand, at a great distance, still appear white, or approaching to a yellowish hue, because they act on our eyes as brightness seen through atmospheric vapour.

8) If a candle flame be held before a white ground, no blue will be seen, but this colour will immediately appear if the flame is opposed to a black ground.

9) Smoke is also to be considered as a semi-transparent medium, which appears to us yellow or reddish before a light ground, but blue before a dark one.

10) Panes of glass throw a yellow light on objects through those parts where they happen to be semi-opaque, and these same parts appear blue if we look at a dark object through them.

11) smoked glass may be also mentioned here, and is, in like manner, to be considered as a semi-opaque medium. It exhibits the sun more or less ruby-coloured; and, although this appearance may be attributed to the black-brown colour of the soot, we may still convince ourselves that a semi-transparent medium here acts if we hold such a glass moderately smoked, and lit by the sun on the unsmoked side, before a dark object, for we shall then perceive a bluish appearance.

12) if we fasten a piece of parchment before the opening in the window-shutter when the sun shines, it will appear nearly white; by adding a second, a yellowish colour appears, which still increases as more leaves are added, till at last it changes to red.

Dioptrical Colours of the Second Class: Refraction (entries 178-194) **– Explanation only**

the medium is in the highest degree transparent. Space is assumed as empty and therefore of absolute transparency. Transparent materials are free from any degree of opacity and direct our whole attention to a phenomenon which here presents itself, and which is known by the name of refraction.

SUBJECTIVE EXPERIMENTS WITH OBJECTIVE EXPLANATION FOLLOWING
Subjective: in which namely, the object is seen by the observer through a refracting medium.
Based on or influenced by personal feelings or opinions.
Objective: require the sun-light, analogous to the SUBJECTIVE experiments. Not influenced by
personal feelings or opinions but in considering facts.
a union of both aspects
Refraction Without the Appearance of Colour (entries 195-196/306-308)

Refraction Without the Appearance of Colour (entries 195-196/306-308) **– 1 experiment:**

1) Place a glass cube on any larger surface, and look through the glass perpendicularly or obliquely, the unbroken surface opposite the eye appears altogether raised, but no colour exhibits itself. If we look at a pure grey or blue sky or a uniformly white or coloured wall through a prism, the portion of the surface which the eye thus embraces will be altogether changed as to its position, without our therefore observing the smallest appearance of colour.
-the sun is the limiting factor (in its size, elevation, intensity). The sun is an object with a boundary shape (it is a circumscribed body) and therefore we are limited to make a solid objective call.

Conditions of the Appearance of Colour (entries 197-208/309-322) **– 5 experiments:**

1) We place before us the simplest object, a light disk on a dark ground. A displacement occurs with regard to this object, if we apparently extend its outline from the centre by magnifying it. This may be done with any convex glass, and in this case we see a blue edge.
2) We can, to appearance, contract the circumference of the same light disk towards the centre by diminishing the object; the edge will then appear yellow. This may be done with a concave glass, which, however, should not be ground thin like common eye-glasses, but must have some substance. In order, however, to make this experiment at once with the convex glass, let a smaller black disk be inserted within the light disk on a black ground. If we magnify the black disk on a white ground with a convex glass, the same result takes place as if we diminished the white disk; for we extend the black outline upon the white, and we thus perceive the yellow edge together with the blue edge.
3) If we cause the white disk to move, in appearance, entirely from its place, which can be done effectually by prisms, it will be coloured according to the direction in which it apparently moves, in conformity with the above laws. If we look at the disk *a* through a prism, so that it appear moved to *b*, the outer edge will appear blue and blue-red, according to the law of the figure *b*, the other edge being yellow, and yellow-red, according to the law of the figure *c*. For in the first case the white figure is, as it were, extended over the dark boundary, and in the other case the dark boundary is passed over the white figure. The same happens if the disk is, to appearance, moved from *a* to *c*, from *a* to *d*, and so throughout the circle.

4) As it is with the simple effect, so it is with more complicated appearances. If we look through a horizontal prism, *ab* **at a white disk placed at some distance behind it at** *e*, **the disk will be raised to** *f*, **and coloured according to the above law. If we remove this prism, and look through a vertical one (***cd***) at the same disk, it will appear at** *h*, **and coloured according to the same law. If we place the two prisms one upon the other, the disk will appear displaced diagonally, in conformity with a general law of nature, and will be coloured as before; that is, according to its movement in the direction** *

5) The quadrangular figure a, moved in the direction *ab*, **or** *ad*, **exhibits no colour on the sides which are parallel with the direction in which it moves: on the other hand, if moved in the direction** *ac*, **parallel with its diagonal, all the edges of the figure appear coloured.**

-water and glass prisms produce the same results

-it is assumed that sun rays are straight lines, so results may vary

-the moon is also a good use of light that can produce same results

<u>Conditions Under Which the Appearance of Colour Increases</u> (entries 209-217/323-334) **– 3 experiments:**

1) If we move a dark boundary towards a light surface, the yellow broader border is foremost, and the narrower yellow-red edge follows close to the outline. If we move a light boundary towards a dark surface, the broader violet border is foremost, and the narrower blue edge follows.

2) if the object is large, its centre remains uncoloured. Its inner surface is then to be considered as unlimited: it is displaced, but not otherwise altered: but if the object is so narrow, that under the above conditions the yellow border can reach the blue edge, the space between the outlines will be entirely covered with colour. If we make this experiment with a white stripe on a black ground, the two extremes will presently meet, and thus produce green. We shall then see the following series of colours:

yellow-red

yellow

green

blue

blue-red

The yellow and blue, in this case, can by degrees meet so fully, that the two colours blend entirely in green, and the order will then be

Yellow-red

green

blue-red

3) If we place a black band, or stripe, on white paper, the violet border will spread till it meets the yellow-red edge. In this case the intermediate black is effaced (as the intermediate white was in the last experiment), and in its stead a splendid pure red will appear. The series of colours will now be as follows:

blue

blue-red

red

yellow-red
yellow
Under similar circumstances, the yellow and blue, in this case, can by degrees meet so fully, that the two colours blend entirely in green, and the order will then be
blue
red
yellow
This appearance is best exhibited by refracting the bars of a window when they are relieved on a grey sky.
-diagrams can be made of these results which indicate solidarity among: oblique direction, changing parallel of prism, increased proportion, distance of recipient surface

Explanation of the Foregoing Phenomena (entries 218-242/335-338) – **1 experiment:**

1) Let a playing-card be held before a mirror. We shall at first see the distinct image of the card, but the edge of the whole card, as well as that of every spot upon it, will be bounded on one side with a border, which is the beginning of the second reflection. This effect varies in different mirrors, according to the different thickness of the glass, and the accidents of polishing.
-shape and circumscription of sun is still the source of light, see issue detailed in prior descriptions
-"semi-transparent" is completely arbitrary and unique to each experience

Decrease of the Appearance of Colour (entries 243-247/339-340) – **Extrapolation only, no experiments described**

Grey Objects Displaced by Refraction (entries 248-257/341) – **4 experiments:**

1) Grey on black, seen through the prism, will exhibit the same appearances as white on black; the edges are coloured according to the same law, only the borders appear fainter. If we relieve grey on white, we have the same edges and borders which would be produced if we saw black on white through the prism.

2) Various shades of grey placed next each other in gradation will exhibit at their edges, either blue and violet only, or red and yellow only, according as the darker grey is placed over or under.

3) A series of such shades of grey placed horizontally next each other will be coloured conformably to the same law according as the whole series is relieved, on a black or white ground above or below.

4) It is of great importance duly to examine and consider another experiment in which a grey object is placed partly on a black and partly on a white surface, so that the line of division

passes vertically through the object.
-subdued materials and shades of grey create equally subdued results

Coloured Objects Displaced by Refraction (entries 258-284/342-344) **– 6 experiments:**

1) If we take a coloured drawing enlarged from the plate, which illustrates this experiment, and examine the red and blue squares placed next each other on a black ground, through the prism as usual, we shall find that as both colours are lighter than the ground, similarly coloured edges and borders will appear above and below, at the outlines of both, only they will not appear equally distinct to the eye.

2) If, for instance, we look at a white square, next the blue one, on a black ground the prismatic hues of the opposite edges of the white, which here occupies the place of the red in the former experiment, will exhibit themselves in their utmost force. The red edge extends itself above the level of the blue almost in a greater degree than was the case with the red square itself in the former experiment. The lower blue edge, again, is visible in its full force next the white, while, on the other hand, it cannot be distinguished next the blue square. The violet border underneath is also much more apparent on the white than on the blue.

3) The edges and their relations to the coloured surfaces appear still more striking if we look at the coloured squares and a black square on a white ground; for in this case the illusion before mentioned ceases altogether, and the effect of the edges is as visible as in any case that has come under our observation. Let the blue and red squares be first examined through the prism. In both the blue edge now appears above; this edge, homogeneous with the blue surface, unites with it, and appears to extend it upwards, only the blue edge, owing to its lightness, is somewhat too distinct in its upper portion; the violet border underneath it is also sufficiently evident on the blue. The apparent blue edge is, on the other hand, heterogeneous with the red square; it is neutralised by contrast, and is scarcely visible; meanwhile the violet border, uniting with the real red, produces a hue resembling that of the peach-blossom.

4) In the instance of a red and blue square on a black ground; in the present experiment the elongation upwards and downwards of two differently coloured figures is apparent in the two halves of one and the same figure of one and the same colour.

5) Let the observer now turn the figures so that the before-mentioned squares placed on the line of division between black and white may be in a horizontal series; the black above, the white underneath. On looking at these squares through the prism, he will observe that the red square now gains by the addition of two red edges; on more accurate examination he will observe the yellow border on the red figure, and the lower yellow border upon the white will be perfectly apparent.

6) Cut in a piece of pasteboard five perfectly similar square openings of about an inch, next each other, exactly in a horizontal line: behind these openings place five coloured glasses in

the natural order, orange, yellow, green, blue, violet. Let the series thus adjusted be fastened in an opening of the camera obscura, so that the bright sky may be seen through the squares, or that the sun may shine on them; they will thus appear very powerfully coloured. Let the spectator now examine them through the prism, and observe the appearances, already familiar by the foregoing experiments, with coloured objects, namely, the partly assisting partly neutralising effects of the edges and borders, and the consequent apparent elongation or reduction of the coloured squares with reference to the horizontal line. The results witnessed by the observer in this case, entirely correspond with those in the cases before analysed; we do not, therefore, go through them again in detail, especially as we shall find frequent occasions hereafter to return to the subject.

-can use a variety of coloured glass
-can use colourless glass and coloured liquid > same results

Achromatism and Hyperchromatism (entries 285-298/345-349) **– 3 experiments:**

1) A black surface is here divided into compartments for more convenient demonstration: let the spectator imagine five white squares between the parallel lines a, b, and c, d. The square No. 1, is presented to the naked eye unmoved from its place.

2) But let the square No. 2, seen through a crown-glass prism g, be supposed to be displaced by refraction three compartments, exhibiting the coloured borders to a certain extent; again, let the square No. 3, seen through a flint glass prism h, in like manner be moved downwards three compartments, when it will exhibit the coloured borders by about a third wider than No. 2.

3) Again, let us suppose that the square No. 4, has, like No. 2, been moved downwards three compartments by a prism of crown-glass, and that then by an oppositely placed prism h, of flint-glass, it has been again raised to its former situation, where it now stands.

-Let the sun's image pass through an acute-angled prism of few degrees, prepared from crown-glass, so that the spectrum be refracted upwards on an opposite surface; the edges will appear coloured, according to the constant law, namely, the violet and blue above and outside, the yellow and yellow-red below and within the image. As the refracting angle of this prism is undermost, let another proportionate prism of flint-glass be placed against it, with its refracting angle uppermost. The sun's image will by this means be again moved to its place, where, owing to the excess of the colouring power of the prism of flint-glass, it will still appear a little coloured, and, in consequence of the direction in which it has been moved, the blue and violet will now appear underneath and outside, the yellow and yellow-red above and inside.

Advantages of Subjective Experiments – Transition to the Objective (entries 299-302) **–**
Explanation only

Refraction Without the Appearance of Colour (entries 195-196/306-308)
Conditions of the Appearance of Colour (entries 197-208/309-322)
Conditions of the Increase of Colour (entries 209-217/323-334)

Achromatism and Hyperchromatism (entries 285-298/345-349) **– 1 experiment:**

1) Let the sun's image pass through an acute-angled prism of few degrees, prepared from crown-glass, so that the spectrum be refracted upwards on an opposite surface; the edges will appear coloured, according to the constant law, namely, the violet and blue above and outside, the yellow and yellow-red below and within the image. As the refracting angle of this prism is undermost, let another proportionate prism of flint-glass be placed against it, with its refracting angle uppermost. The sun's image will by this means be again moved to its place, where, owing to the excess of the colouring power of the prism of flint-glass, it will still appear a little coloured, and, in consequence of the direction in which it has been moved, the blue and violet will now appear underneath and outside, the yellow and yellow-red above and inside.

Combination of Subjective and Objective Experiments (entries 350-356) **– 1 experiment:**

1) Let the sun's image be thrown upwards on a vertical plane, through a horizontally-placed prism. If the prism is long enough to admit of the spectator also looking through it, he will see the image elevated by the objective refraction again depressed, and in the same place in which it appeared without refraction.
-looking upwards and downwards through the prism satisfies both subjective and objective laws as detailed in above experiments

Transition (entries 357-365) **– Explanation only**

Catoptrical Colours (entries 366-388) **– 5 experiments:**

1) If we unroll a coil of bright steel-wire, and after suffering it to spring confusedly together again, place it at a window in the light, we shall see the prominent parts of the circles and convolutions illumined, but neither resplendent nor iridescent. But if the sun shines on the wire, this light will be condensed into a point, and we perceive a small resplendent image of the sun, which, when seen near, exhibits no colour. On retiring a little, however, and fixing the eyes on this refulgent appearance, we discern several small mirrored suns, coloured in the most varied manner; and although the impression is that green and red predominate, yet, on a more accurate inspection, we find that the other colours are also present.

2) If we take an eye-glass, and examine the appearance through it, we find the colours have vanished, as well as the radiating splendour in which they were seen, and we perceive only the small luminous points, the repeated images of the sun. We thus find that the impression is subjective in its nature, and that the appearance is allied to those which we have adverted

to under the name of radiating halos.

3) Let a piece of white paper be fastened beneath a small aperture in the lid of a camera-obscura, and when the sun shines through this aperture, let the confusedly-rolled steel-wire be held in the light, so that it be opposite to the paper. The sun-light will impinge on and in the circles of the wire, and will not, as in the concentrating lens of the eye, display itself in a point; but, as the paper can receive the reflection of the light in every part of its surface will be seen in hair-like lines, which are also iridescent.

4) A polished surface of silver placed in the sun reflects a dazzling light, but in this case no colour is seen. If, however, we slightly scratch the surface, an iridescent appearance, in which green and red are conspicuous, will be exhibited at a certain angle. In chased and carved metals the effect is striking: yet it may be remarked throughout that, in order to its appearance, some form, some alternation of light and dark must co-operate with the reflection; thus a window-bar, the stem of a tree, an accidentally or purposely interposed object produces a perceptible effect. This appearance, too, may be exhibited objectively in the camera-obscura.

5) If we cause a polished plated surface to be so acted on by aqua fortis that the copper within is touched, and the surface itself thus rendered rough, and if the sun's image be then reflected from it, the splendour will be reverberated from every minutest prominence, and the surface will appear iridescent. So, if we hold a sheet of black unglazed paper in the sun, and look at it attentively, it will be seen to glisten in its minutest points with the most vivid colours.

Paroptrical Colours (entries 389-428) – **7 experiments:**

1) A person walking in sun-shine in a garden, or on any level path, may observe that his shadow only appears sharply defined next the foot on which he rests; farther from this point, especially round the head, it melts away into the bright ground. For as the sun-light proceeds not only from the middle of the sun, but also acts cross-wise from the two extremes of every diameter, an objective parallax takes place which produces a half-shadow on both sides of the object.

2) The experiment may be repeated and varied before a smooth wall, with rods of different thicknesses, and again with balls; we shall always find that the farther the object is removed from the surface of the wall, the more the weak double shadow spreads, and the more the forcible main shadow diminishes, till at last the main shadow appears quite effaced, and even the double shadows become so faint, that they almost disappear; at a still greater distance they are, in fact, imperceptible.

3) Instead of solid bodies let us now take openings cut of various given sizes next each other, and let the sun shine through them on a plane surface at some little distance; we shall find that the bright image produced by the sun on the surface, is larger than the opening; this is

because one edge of the sun shines towards the opposite edge of the opening, while the other edge of the disk is excluded on that side. Hence the bright image is more weakly lighted towards the edges.

4) Let a small opening be made in the window-shutter of a dark room; let the crossing sun-light which enters, be received on a surface of white paper, and we shall find that the smaller the opening is, the dimmer the light image will be. This is quite obvious, because the paper does not receive light from the whole sun, but partially from single points of its disk.

5) If we take a somewhat larger square opening, so large that the image of the sun shining through it does not immediately become round, we may distinctly observe the half-shadows of every edge or side, the junction of these in the corners, and their colours; just as in the above-mentioned appearance with the round opening.

6) If we hold a ruler before the eyes so that the flame of a light just appears above it, we see the ruler as it were indented and notched at the place where the light appears. This seems deducible from the expansive power of light acting on the retina.

7) The same phenomenon on a large scale is exhibited at sun-rise; for when the orb appears distinctly, but not too powerfully, so that we can still look at it, it always makes a sharp indentation in the horizon.

Epoptical Colours (entries 429-485) **– Explanation only; no experiments described**
-heating metals give a fleeting array of colour as their temperature changes under the influence of heat
-surfaces of bubbles under all sorts of light acting on them reveal iridescent colours
-breathing on glass fogs it up and we see an array of colours which disappear with evaporation

***

Part III
Part III is chaptered as such:
To know:
Colour which we can produce is a chemical colour. Colour becomes fixed in bodies permanently; superficially, or thoroughly. Acid and alkali provide colour: yellow and yellow-red correspond to acid, blue and blue-red correspond to alkali. We see this in the oxidation of metals.
Observations on minerals affected by the "excitation" of heat, chemicals, oxydation. The change one sees in colour on litmus. The mixing of paint colours to produce grey, combining coloured glass to see different effects, the bleaching or extracting of colour from water and the sun. Also notes on colour in nature: Minerals, Plants, Worms, Insects, Fishes, Birds, Mammalia and Human Beings.

Chemical Contrast (entries 486-493) **– Explanation only, no experiments described**

White (entries 497) **– Explanation only, no experiments described**

Black (entries 498-500) **– Explanation only, no experiments described**

First Excitation of Colour (entries 501-516) **– Explanation only, no experiments described**

Augmentation of Colour (entries 517-522) **– 2 experiments:**

Steigerung, literally *gradual ascent*. This is the consequence of still progressing augmentation. Red, in which neither yellow nor blue is to be detected, here constitutes the acme. An ascent through yellow and blue to red.

To know: The augmentation of colour exhibits itself as a condensation, a fulness, a darkening of the hue. We have before seen, in treating of colourless mediums, that by increasing the degree of opacity in the medium, we can deepen a bridge object from the lightest yellow to the intensest ruby-red. Blue, on the other hand, increases to the most beautiful violet, if we rarefy and diminish a semi-opaque medium, itself lighted, but through which we see darkness.

1) If the colour is positive, a similar colour appears in the intenser state. Thus if we fill a white porcelain cup with a pure yellow liquor, the fluid will appear to become gradually redder towards the bottom, and at last appears orange.

2) If we pour a blue solution into another cup, the upper portion will exhibit a sky-blue, that towards the bottom, a beautiful violet.

Culmination (entries 523-530) **– Explanation only, no experiments described**

Fluctuation (entries 531-533) **– Explanation only, no experiments described**

Passage Through the Whole Scale (entries 534-540) **– Explanation only, no experiments described**

Inversion (entries 541-544) **– Explanation only, no experiments described**

Fixation (entries 545-550) **– Explanation only, no experiments described**

Intermixture, Real (entries 551-559) **– Explanation only, no experiments described**

Intermixture, Apparent (entries 560-571) **– Explanation only, no experiments described**

Communication, Actual (entries 572-587) **– Explanation only, no experiments described**

Communication, Apparent (entries 588-592) **– 1 experiment:**

1) Let a surface coloured with any one of the positive colours be placed in the sun, and let its reflection be thrown on other colourless objects. This reflection is kind of subdued light, a half-light, a half-shadow, which, in a subdued state, reflects the colours in question.

Extraction (entries 593-604) **– Explanation only, no experiments described**

Nomenclature (entries 605-612) **– Explanation only, no experiments described**

Minerals, Plants, Worms, Insects, Fishes, Birds, Mammalia and Human Beings (entries 613-672) **– Explanation only, no experiments described**

Physical and Chemical Effects of the Transmission of Light Through Coloured Mediums (entries 673-681)
– Explanation only, no experiments described

Chemical Effect in Dioptrical Achromatism (entries 682-687) **– Explanation only, no experiments described**

Appendix 2

| Experiment (numbering in tandem with Vimeo numbering)	Object(s) created and details	Materials used and details	Light(s) used and details	Cameras used and d...
Part I: Physiological Colours				
Effects of Black and White Objects on the Eye				
1_1) Effects of Black and White Objects on the Eye	2 polygon planes adjacent, scale of 5 Maya units. 2 polygon disks translated from planes at 0.005 in +Z, scale of 1 Maya units	AiStandardSurface, white and black. Settings unaltered from default	AiSkyDomeLight; settings unaltered from default	Maya camera; focal 35; settings unaltere... default
2_2) Effects of Black and White Objects on the Eye	1 polygon cube, height of 1, width of 0.7, depth of 0.25. Animated over 100 frames from screen L to R	AiStandardSurface, 50% grey. Settings unaltered from default	AiAreaLight; disk scale of 1. Settings unaltered from default	Maya camera; focal 35; settings unaltere... default
3_3) Effects of Black and White Objects on the Eye	1 polygon plane, scale of 12	AiStandardSurface, 50% grey. Settings unaltered from default	AiAreaLight; disk scale of 1. Settings unaltered from default. Animated over 100 frames over 4 Maya units in +Y	Maya camera; focal 35; settings unaltere... default
4_4) Effects of Black and White Objects on the Eye	2 polygon planes forming intersecting window bars, span of 11 Maya units. 1 polygon plane, trans 35 Maya units in -Z	AiStandardSurface, 50% grey. Settings unaltered from default. AiStandardSurface, white. Emission weight of 1. All other settings unaltered from default	n/a	Maya camera; focal 35; settings unaltere... default
5_5) Effects of Black and White Objects on the Eye	n/a	AiStandardSurface, white. Emission weight of 1. All other settings unaltered from default	n/a	Maya camera; focal 35; settings unaltere... default
6_6) Effects of Black and White Objects on the Eye	2 polygon planes forming intersecting window bars, span of 11 Maya units. 1 polygon plane, trans 35 Maya units in -Z	AiStandardSurface, 50% grey. Settings unaltered from default	AiSkyDomeLight; settings unaltered from default	Maya camera; focal 35; settings unaltere... default
7_7) Effects of Black and White Objects on the Eye	1 polygon plane, scale of 5 Maya units. 1 polygon disk translated from plane at 0.005 in +Z, scale of 1 Maya units	AiStandardSurface, 50% grey and black. Settings unaltered from default	AiSkyDomeLight; settings unaltered from default	Maya camera; focal 35; settings unaltere... default
Grey Surfaces and Objects				
8_1) Grey Surfaces and Objects	1 polygon plane, scale of 12 Maya units. 1 polygon disk translated from plane at 0.005 in +Z, scale of 1 Maya units	AiStandardSurface, 50% grey and black. Settings unaltered from default	AiSkyDomeLight; settings unaltered from default	Maya camera; focal 35; settings unaltere... default
9_2) Grey Surfaces and Objects	1 polygon plane, scale of 12 Maya units. 1 polygon disk translated from plane at 0.005 in +Z, scale of 1 Maya units	AiStandardSurface, 50% grey and white. Settings unaltered from default	AiSkyDomeLight; settings unaltered from default	Maya camera; focal 35; settings unaltere... default
10_3) Grey Surfaces and Objects	2 polygon planes adjacent, scale of 5 Maya units. 2 polygon disks translated from planes at 0.005 in +Z, scale of 1 Maya units	AiStandardSurface, 50% grey and black. Settings unaltered from default	AiSkyDomeLight; settings unaltered from default	Maya camera; focal 35; settings unaltere... default
Dazzling Colourless Objects				
11_1) Dazzling Colourless Objects	1 polygon cube as Room, with tesselation for open window. 1 man character to scale	AiStandardSurface, 50% grey and white. Settings unaltered from default	AiSkyDomeLight; settings unaltered from default	Maya camera; focal 35; settings unaltere... default
12_2) Dazzling Colourless Objects	1 polygon cube as Room, with tesselation for open window. 1 man character to scale	AiStandardSurface, 50% grey and white. Settings unaltered from default	2 AiAreaLights adjacent; scale of 143x95 Maya units. Intensity 150000	Maya camera; focal 35; settings unaltere... default
13_3) Dazzling Colourless Objects	1 polygon cube as Room, with tesselation for open window. 1 man character to scale. 2 polygon planes adjacent, scale of 5 Maya units	AiStandardSurface, 50% grey, black, and white. Settings unaltered from default	2 AiAreaLights adjacent; scale of 143x95 Maya units. Intensity 150000	Maya camera; focal 35; settings unaltere... default
Coloured Objects				
14_1) Coloured Objects	1 polygon plane, scale of 35 Maya units. 1 polygon plane made dynamic, scale of 2.3 Maya units	AiStandardSurface, white, settings unaltered from default. AiStandardSurface, Prussian blue, colourpicked from http://www.webexhibits.org/pigments/indiv/history/prussblue.html#	AiSkyDomeLight; settings unaltered from default	Maya camera; focal 35; settings unaltere... default
15_2) Coloured Objects	2 polygon planes, scale of 35 Maya units. 1 man character to scale	AiStandardSurface, 50% grey, black, red, and white. Settings unaltered from default	AiSkyDomeLight; settings unaltered from default. Maya spotlight, quadratic decay, intensity of 500, placed 10 Maya units behind camera	Maya camera; focal 35; settings unaltere... default
16_4) Coloured Objects	2 polygon planes, scale of 35 Maya units	AiStandardSurface, 50% grey. Settings unaltered from default. AiStandard Surface, transmission value of 0.75. Animated over 10 frames in -Z , colourpicked from Tait, H., 1991. Five Thousand Years of Glass. British Museum Press, London.	AiSkyDomeLight; settings unaltered from default	Maya camera; focal 35; settings unaltere... default
17_5) Coloured Objects	2 polygon planes adjacent, scale of 35 Maya units. 2 polygon planes translated from planes at 0.005 in +Z, scale of 2.3 Maya units	AiStandardSurface, white and yellow. Settings unaltered from default	AiSkyDomeLight; settings unaltered from default	Maya camera; focal 35; settings unaltere... default
18_6) Coloured Objects	2 polygon house-shapes, adjacent, scale of 5 Maya units. 16 polygon rectangles, placed 0.5 Maya units apart, width of 1, height of 9 Maya units	AiStandardSurface, 50% grey, red and green. Settings unaltered from default	AiSkyDomeLight; settings unaltered from default	Maya camera; focal 35; settings unaltere... default
19_7) Coloured Objects	1 polygon plane, scale of 35 Maya units. 1 polygon plane translated at 0.005 in +Z, scale of 2.3 Maya units	AiStandardSurface, white and orange. Settings unaltered from default	AiSkyDomeLight; settings unaltered from default	Maya camera; focal 35; settings unaltere... default
Coloured Shadows				
20_1) Coloured Shadows	1 polygon plane, scale of 155 Maya units. 1 polygon rectangle, height of 36 Maya units. Sitting on plane, upright	AiStandardSurface, 50% grey. Settings unaltered from default	2 AiAreaLights, scale of 15 Maya units each. Intensity 3000. AiPhysicalSky; settings unaltered from default	Maya camera; focal 35; settings unaltere... default
21_2) Coloured Shadows	1 polygon plane, scale of 2000 Maya units. 2 polygon cylinders, height of 2 Maya units	AiStandardSurface, white. Settings unaltered from default	1 AiAreaLight, scale of 10 Maya units, placed at the perimeter of the AiPhysicalSky dome; settings unaltered from default. AiMeshLight, intensity of 5.5, ramp of blue to orange, Exposure 2.5, Colour Temperature 1500 Kelvin; candle light	Maya camera; focal 35; settings unaltere... default
22_3) Coloured Shadows	1 polygon plane, scale of 2000 Maya units. 1 polygon plane, scale of 0.8 Maya units. 3 polygon cylinders, height of 2 Maya units	AiStandardSurface, white. Settings unaltered from default. AiStandard Surface, Transmission Weight of 0.75	AiMeshLight, intensity of 5.5, ramp of blue to orange, Exposure 2.5, Colour Temperature 1500 Kelvin; candle light	Maya camera; focal 35; settings unaltere... default
23_4) Coloured Shadows	1 polygon plane, scale of 2000 Maya units. 1 polygon cylinder, height of 2 Maya units	AiStandardSurface, white. Settings unaltered from default	AiMeshLight, intensity of 5.5, ramp of blue to orange, Exposure 2.5, Colour Temperature 1500 Kelvin; candle light, AiPhysicalSky, settings unaltered from default	Maya camera; focal 35; settings unaltere... default
24_5) Coloured Shadows	1 polygon plane, scale of 2000 Maya units. 1 polygon plane, 17 Maya units. 1 polygon cylinder, height of 2 Maya units, 1 polygon cone, scale of 1 Maya units	AiStandardSurface, 50% grey and white. Settings unaltered from default	AiMeshLight, intensity of 5.5, ramp of blue to orange, Exposure 2.5, Colour Temperature 1500 Kelvin; candle light, AiPhysicalSky, settings unaltered from default	Maya camera; focal 35; settings unaltere... default
Faint Lights				
25_1) Faint Lights	1 polygon cylinder, height of 2 Maya units. 1 polygon cube as Room, with tesselation for open window. 1 man character to scale. 3 polygon planes, scale of 5 Maya units	AiStandardSurface, 50% grey and white. Settings unaltered from default	AiMeshLight, intensity of 5.5, ramp of blue to orange, Exposure 2.5, Colour Temperature 1500 Kelvin; candle light	Maya camera; focal 35; settings unaltere... default
			AiMeshLight, intensity of 5.5, ramp of blue to orange,	Maya camera; focal ...

Appendix 3

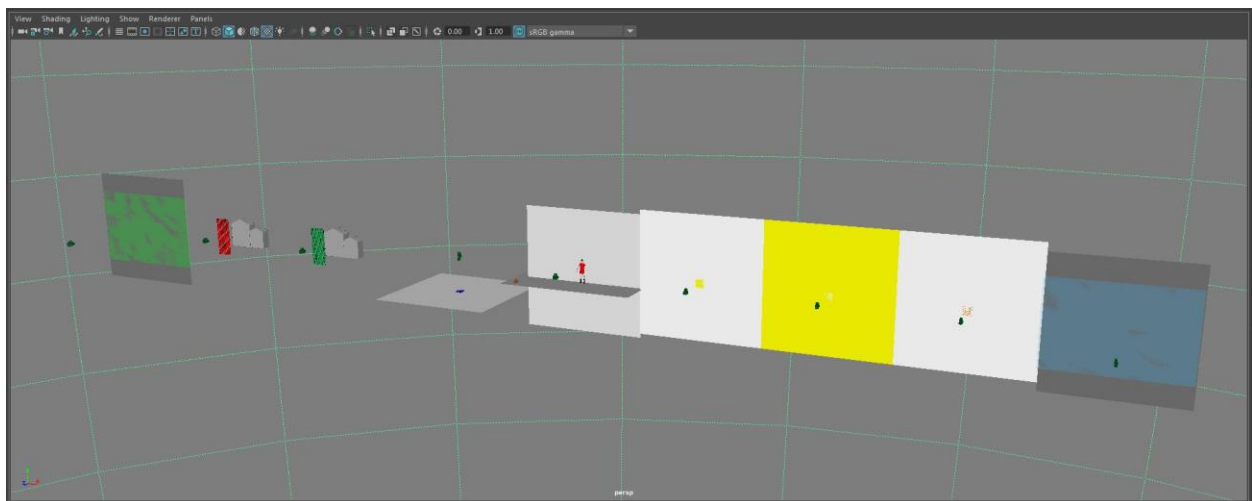**Images of 3D Maya viewports with described chapters and/or experiments:**
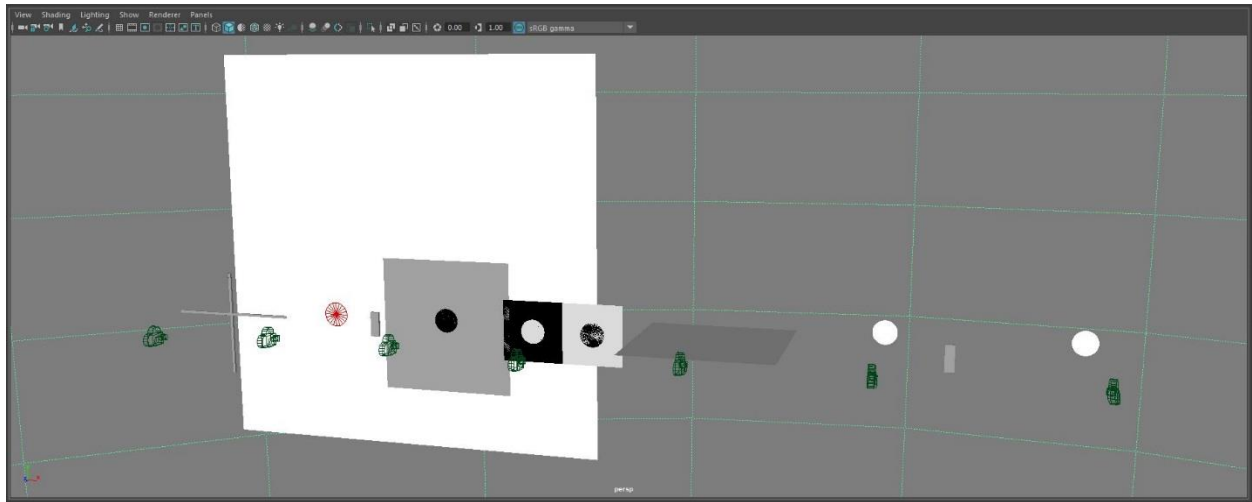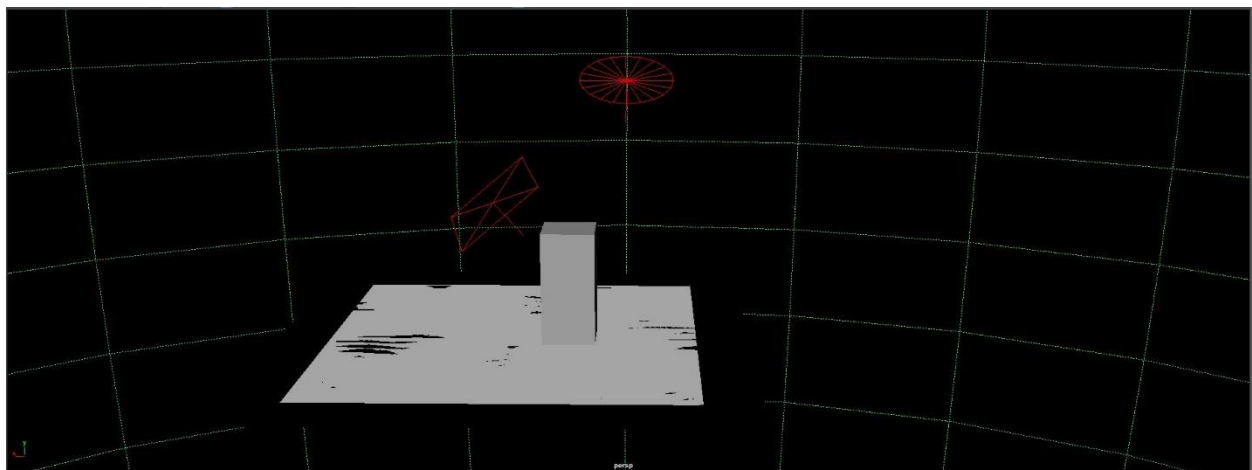

Effects of Black and White Objects on the Eye (1-7)
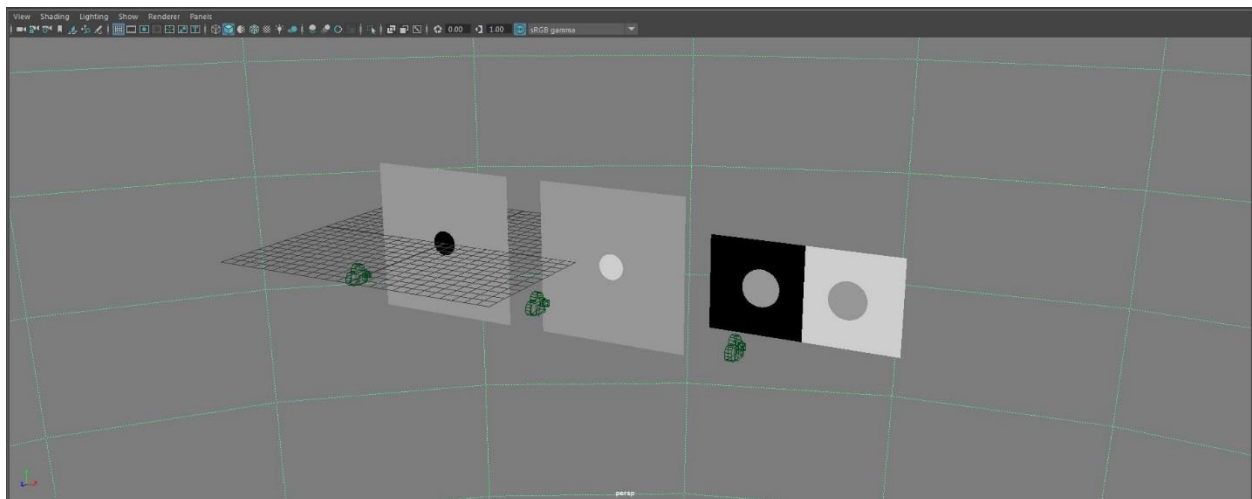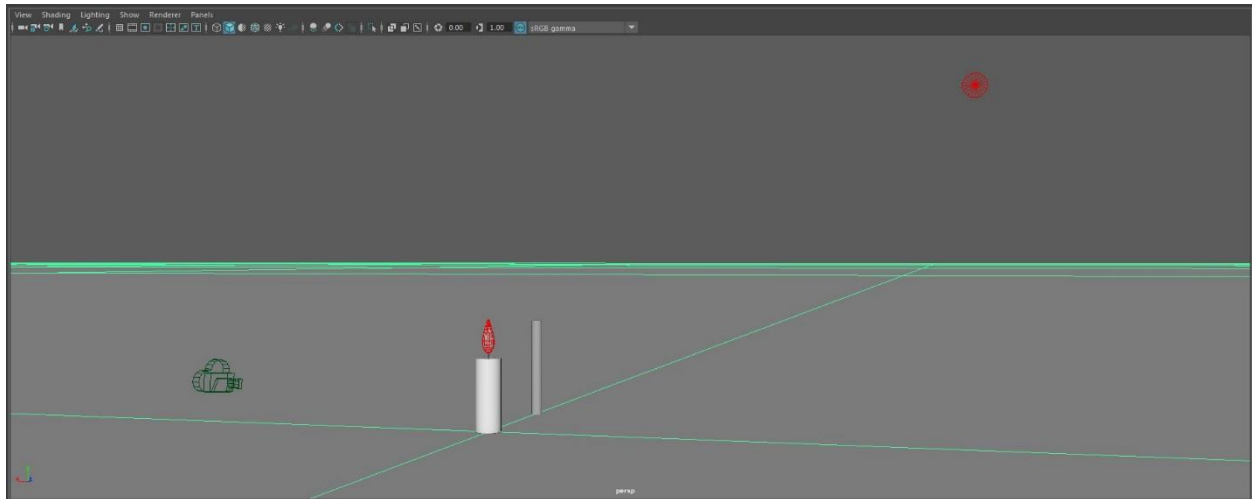

Grey Surfaces and Objects (8-10)
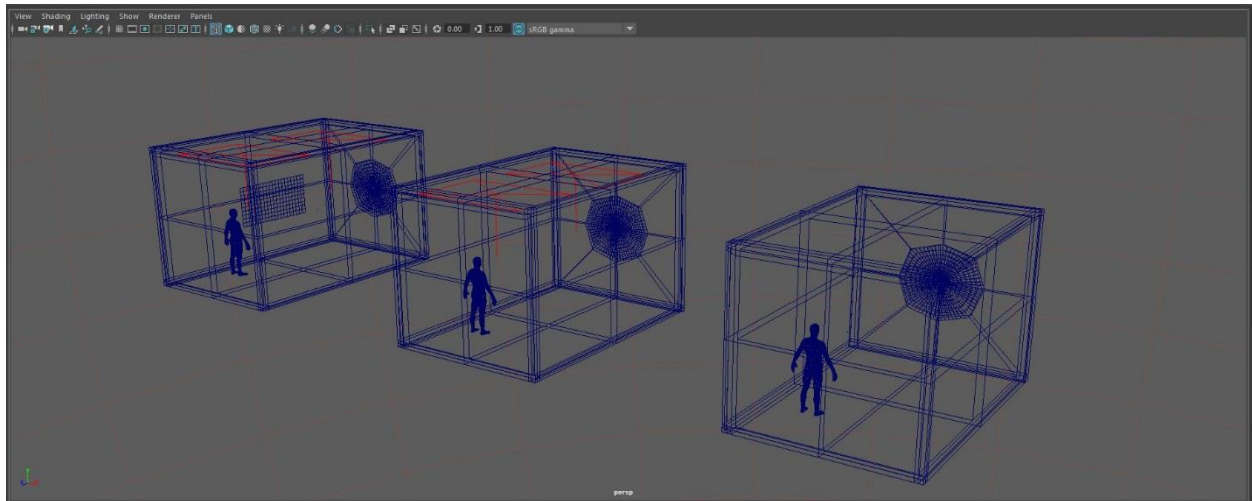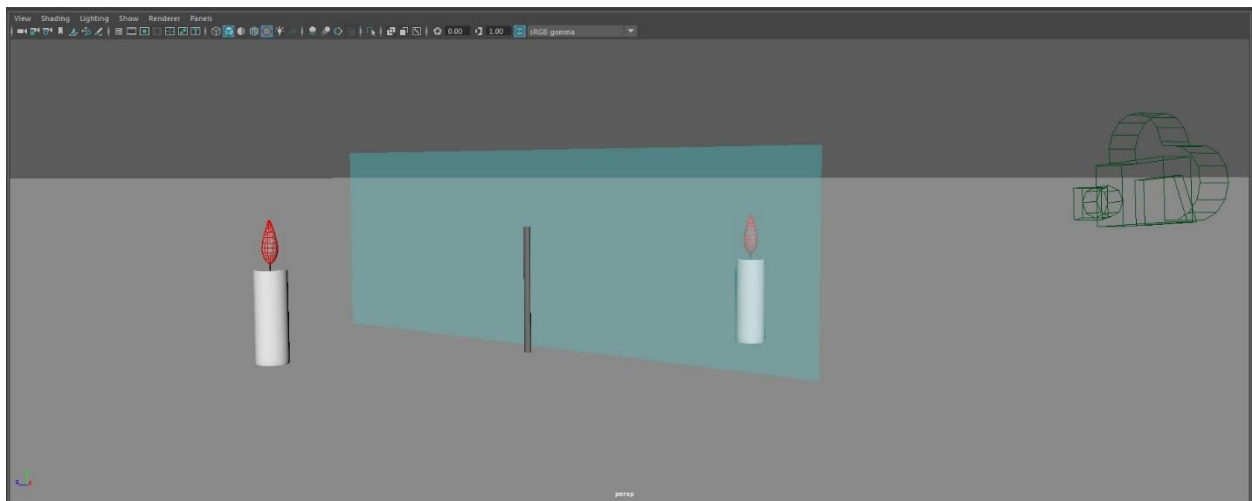
Dazzling Colourless Objects (11-13)
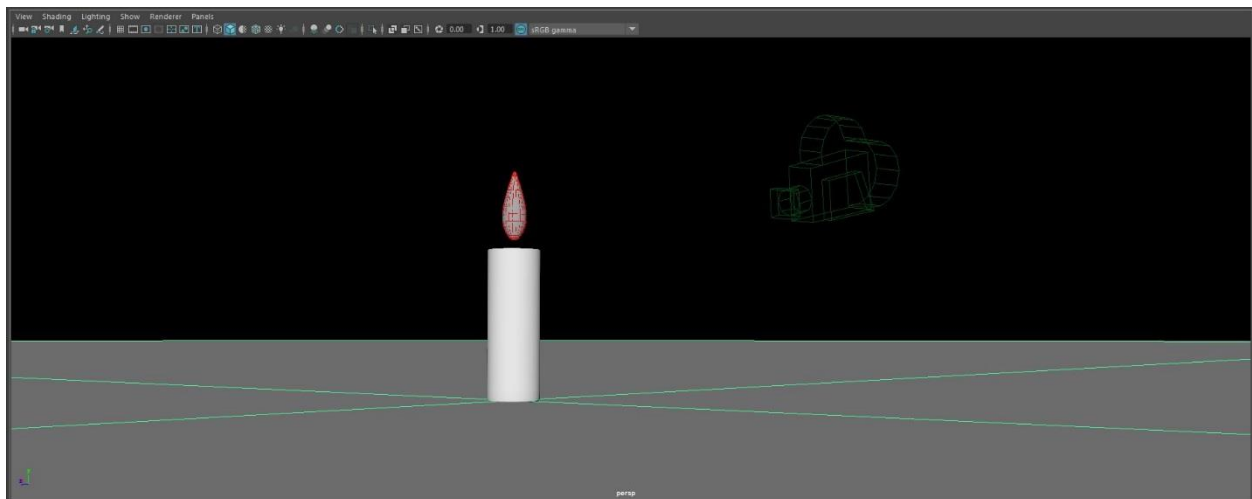

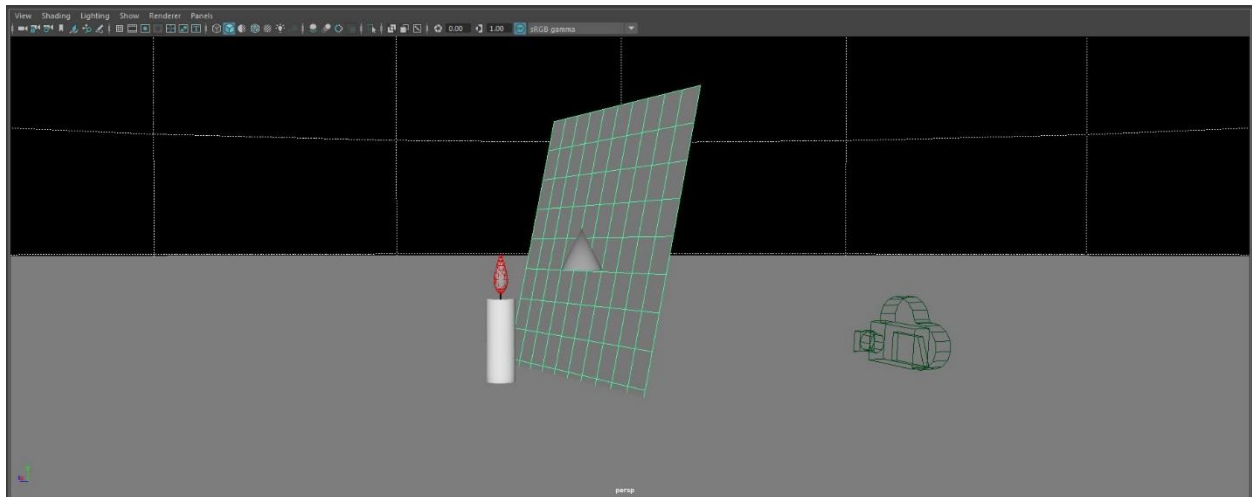Coloured Objects (14-19)

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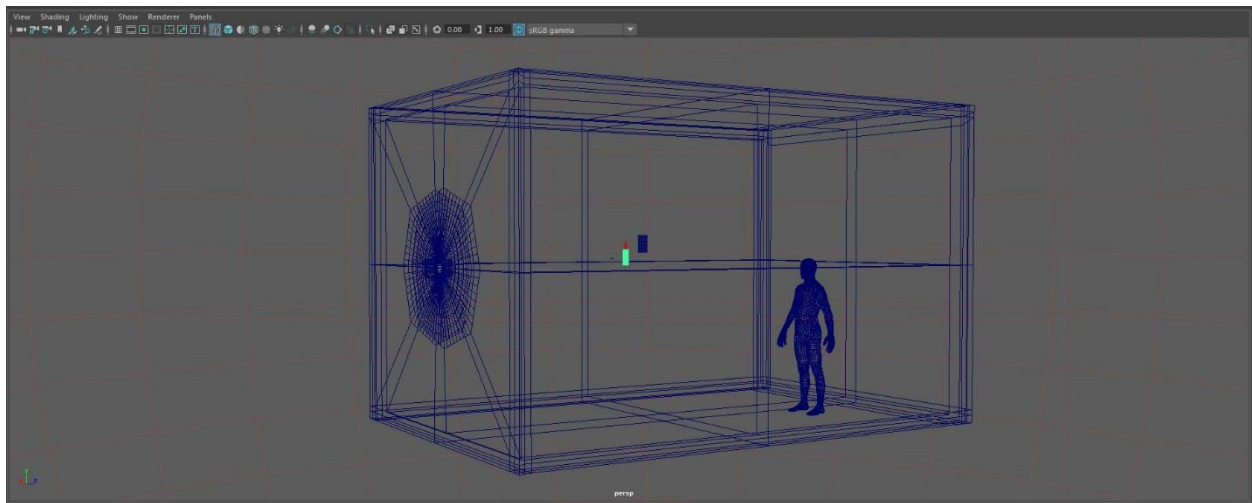
21_2) Coloured Shadows
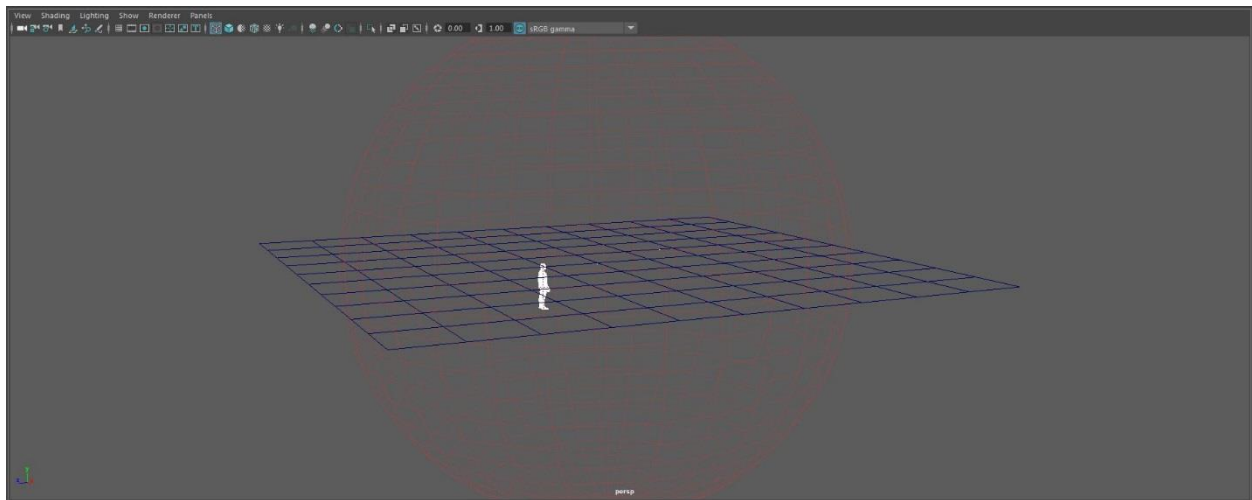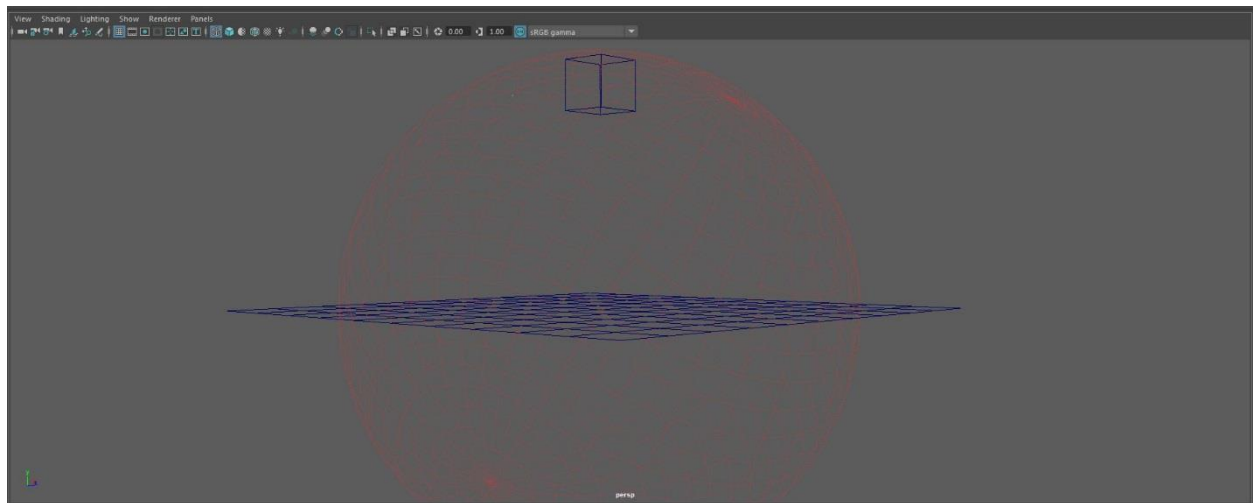

22_3) Coloured Shadows
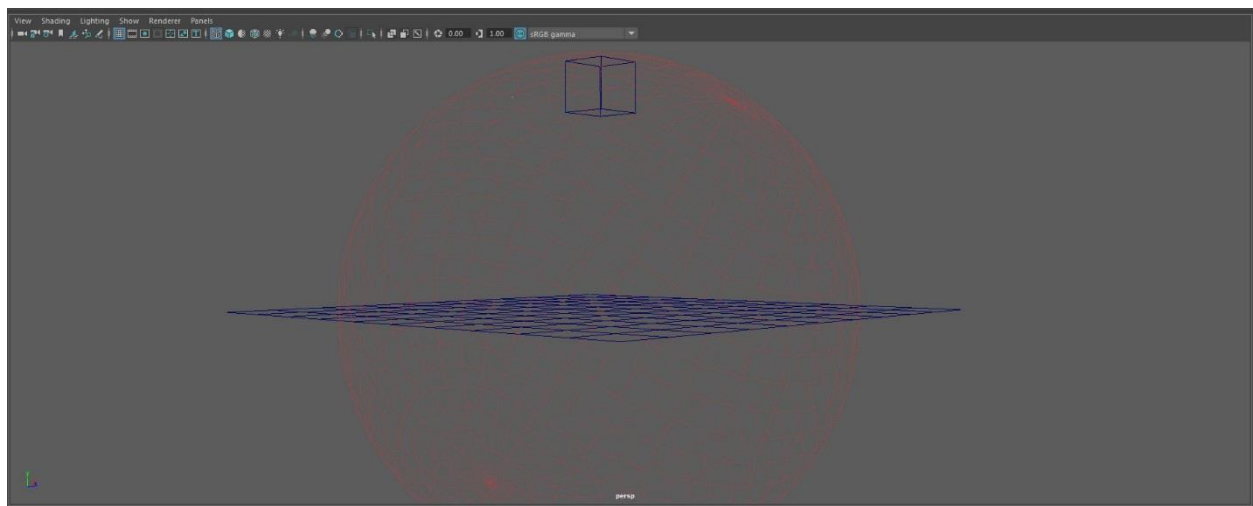

23_4) Coloured Shadows

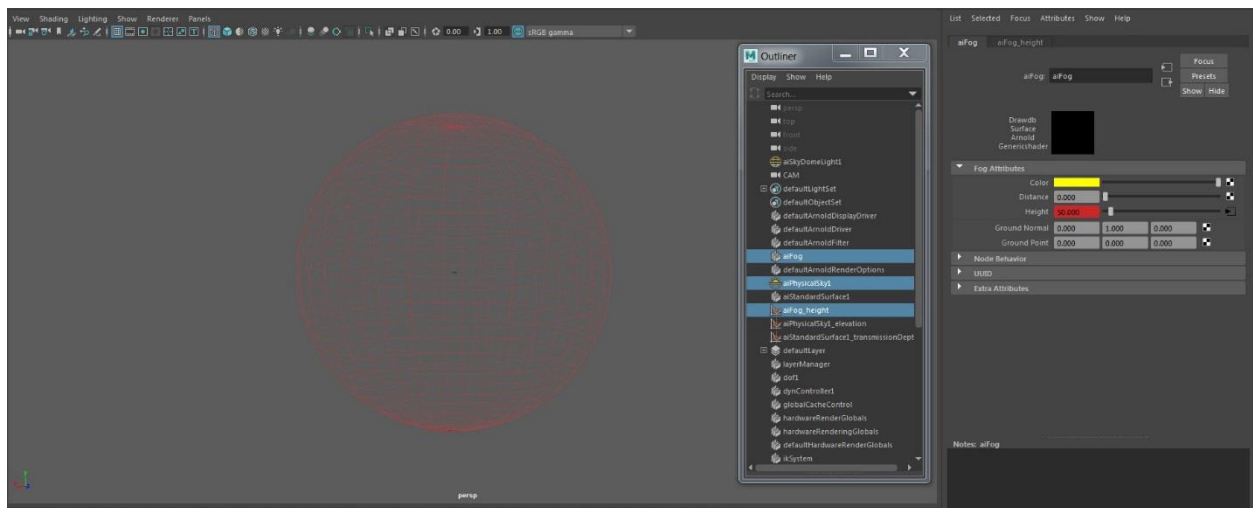24_5) Coloured Shadows

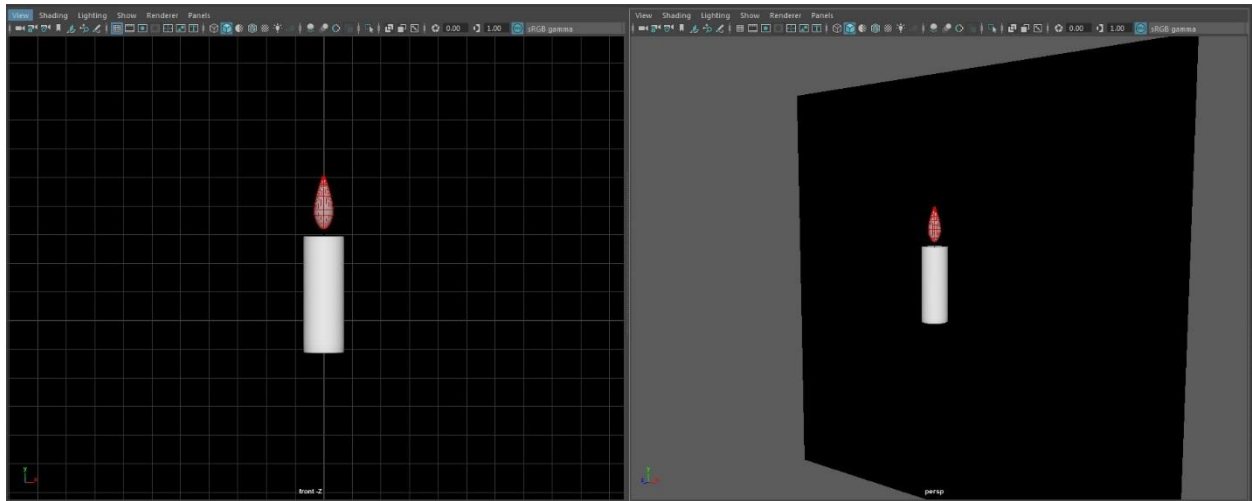Faint Lights (25-28)

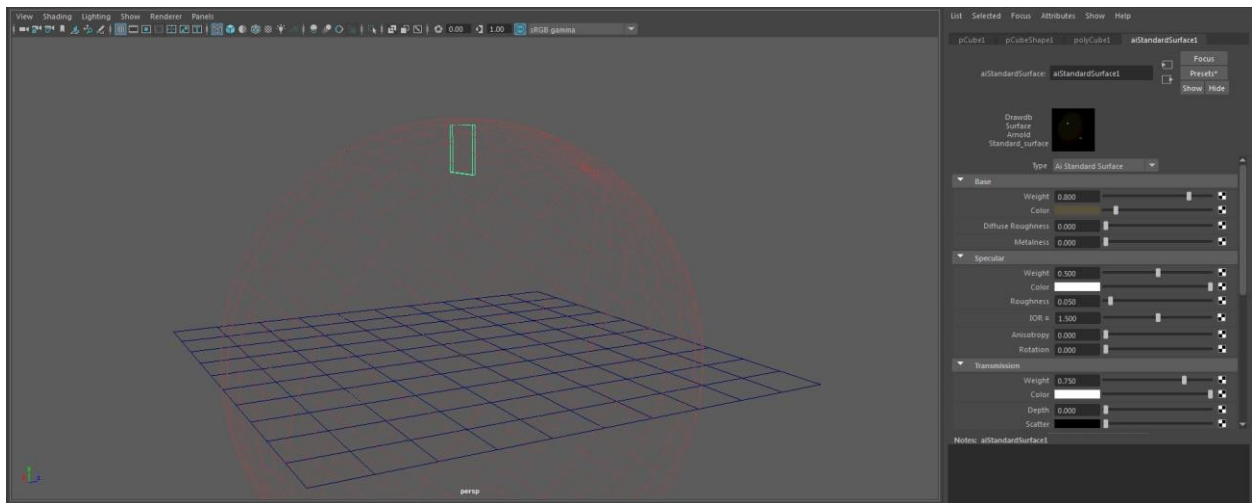Subjective Halos (29-30)

31_1) Dioptrical Colours of the First Class

32_2) Dioptrical Colours of the First Class

33_3 & b) Dioptrical Colours of the First Class

36_8) Dioptrical Colours of the First Class

37_11) Dioptrical Colours of the First Class
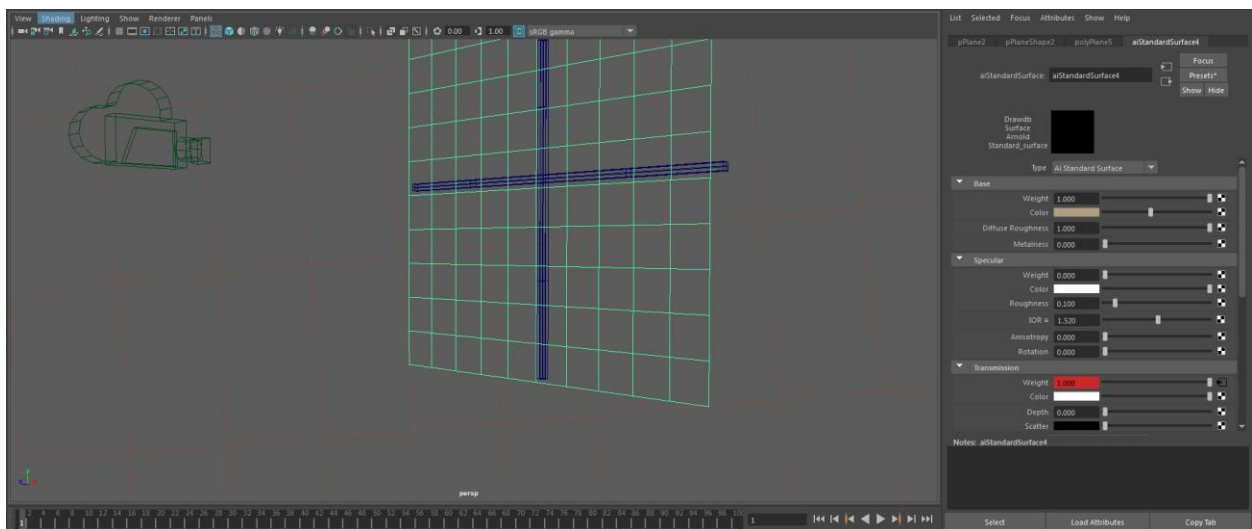
38_12) Dioptrical Colours of the First Class
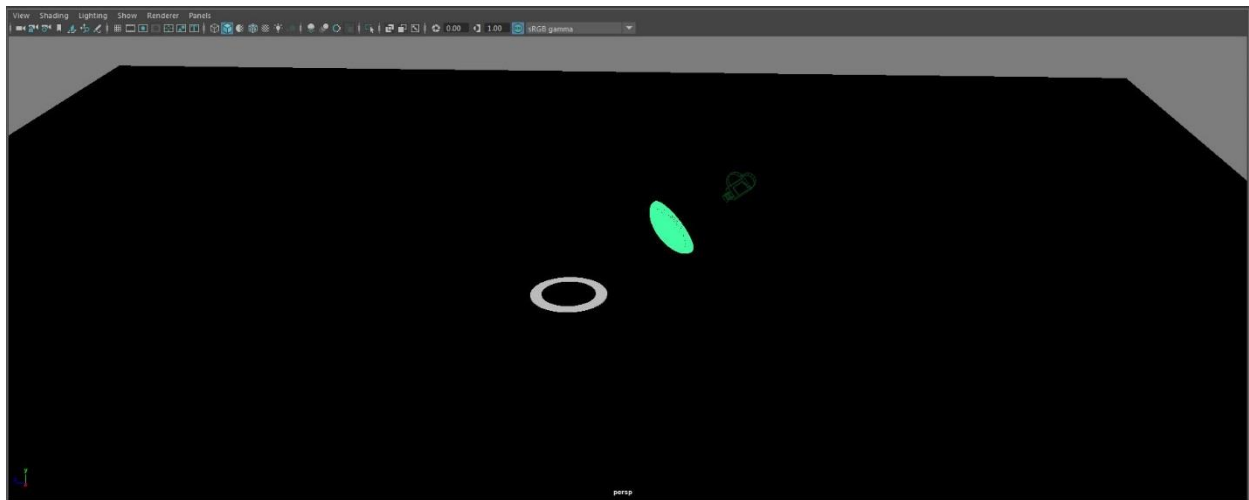
39_1) Conditions of the Appearance of Colour
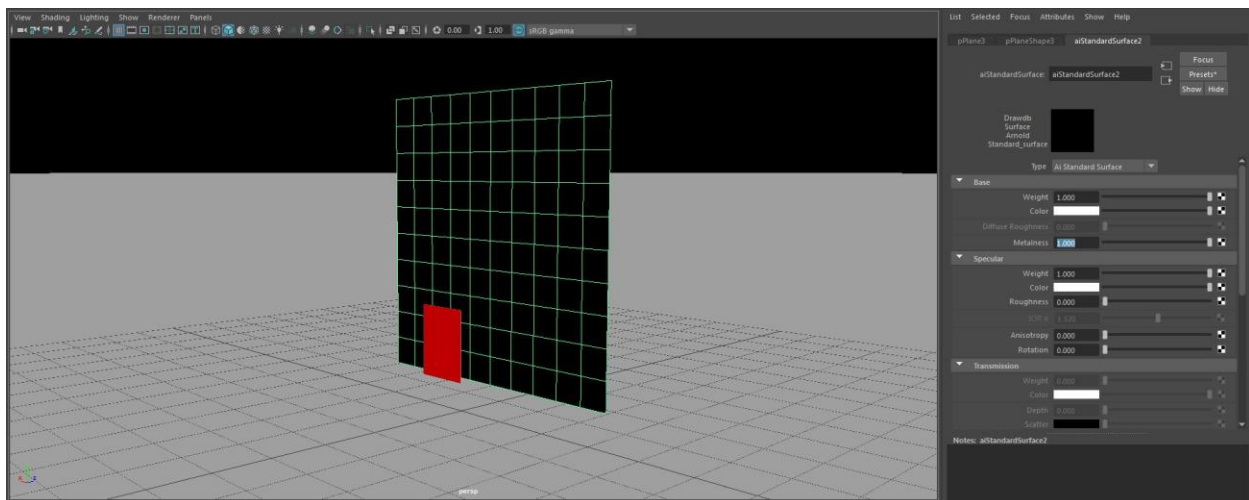
40_1) Explanation of the Foregoing Phenomena
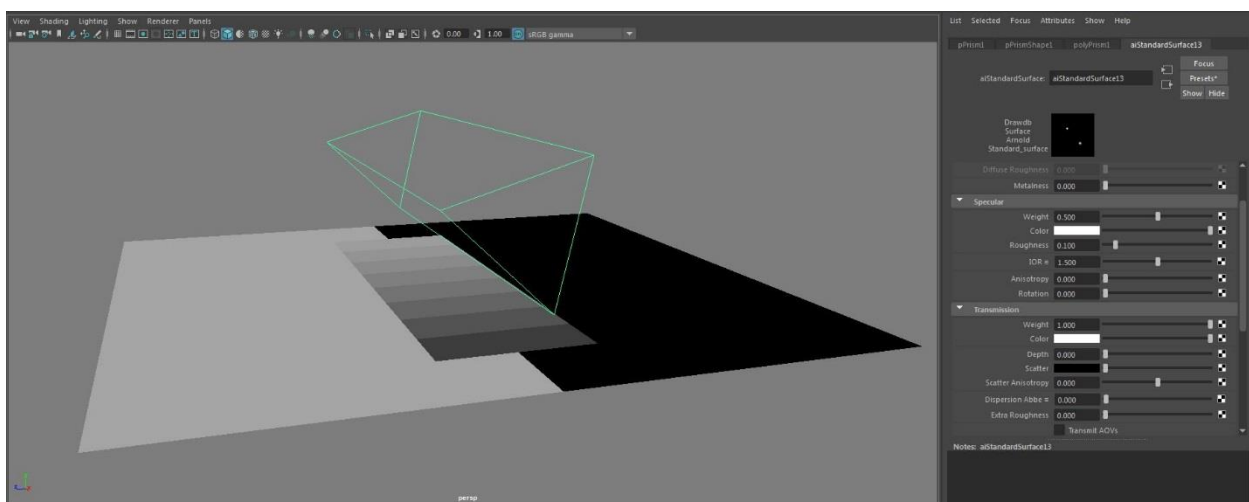
41_1) Grey Objects Displaced by Refraction
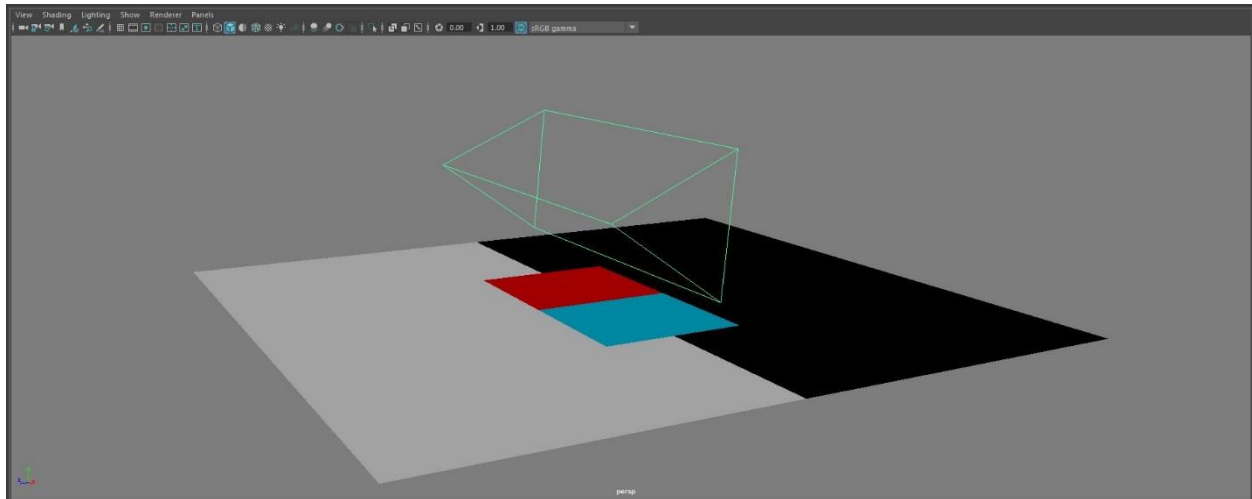
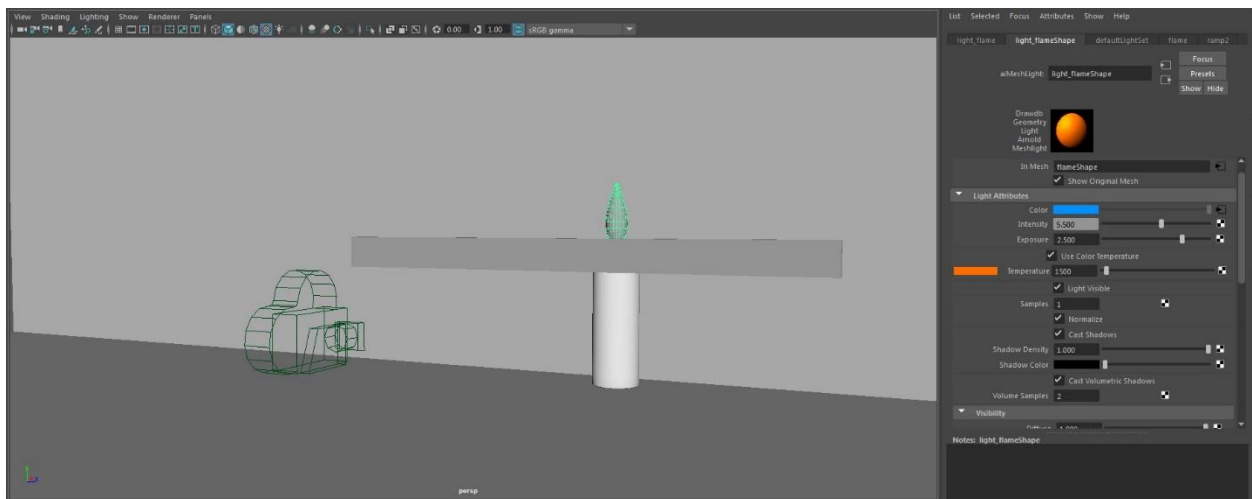42_1) Coloured Objects Displaced by Refraction
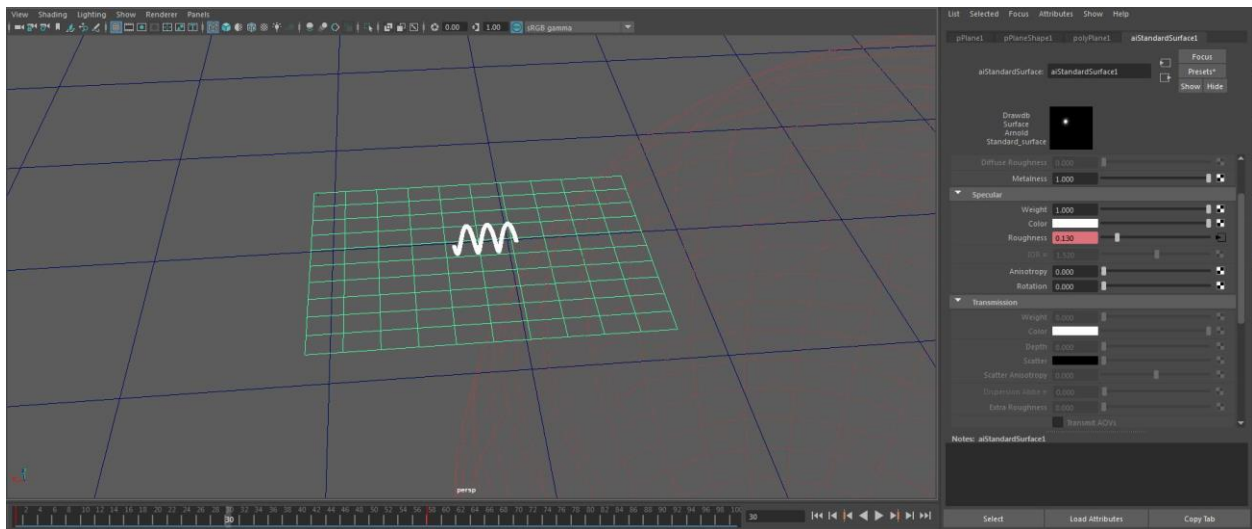
43_1) Catoptrical Colours
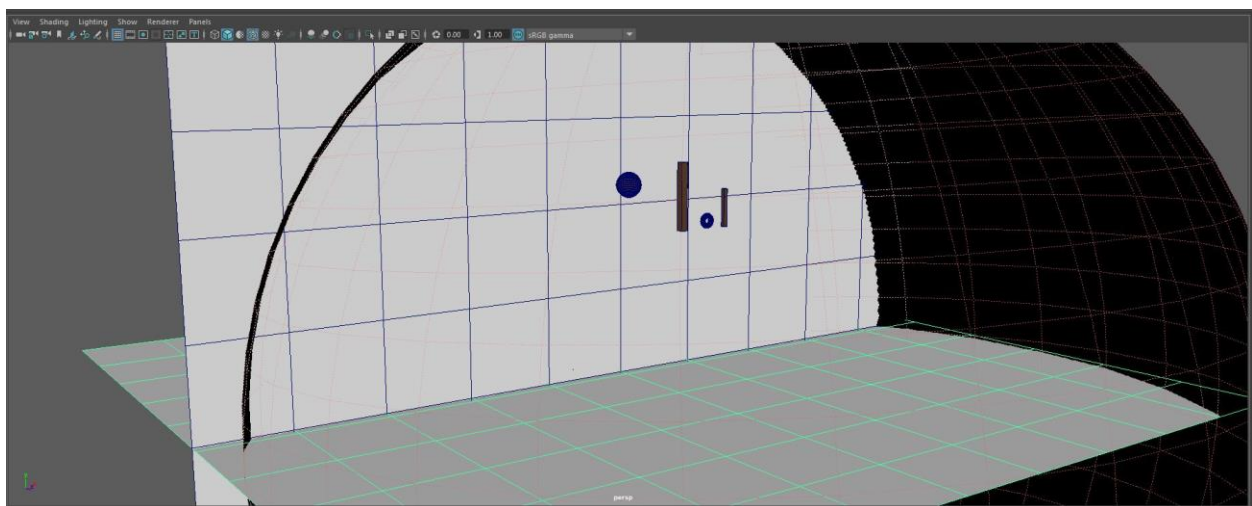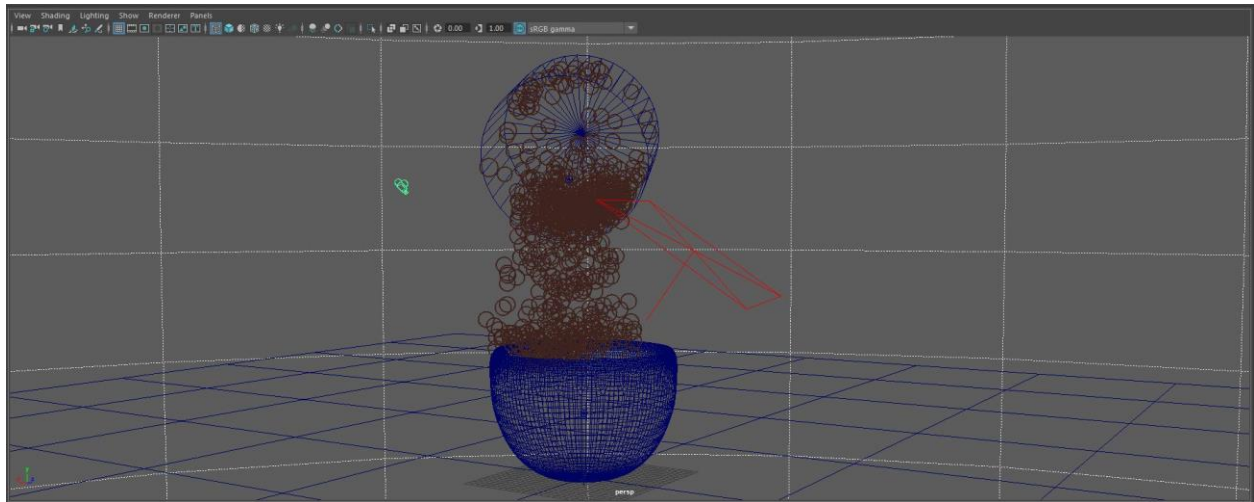

44_1) Paroptrical Colours
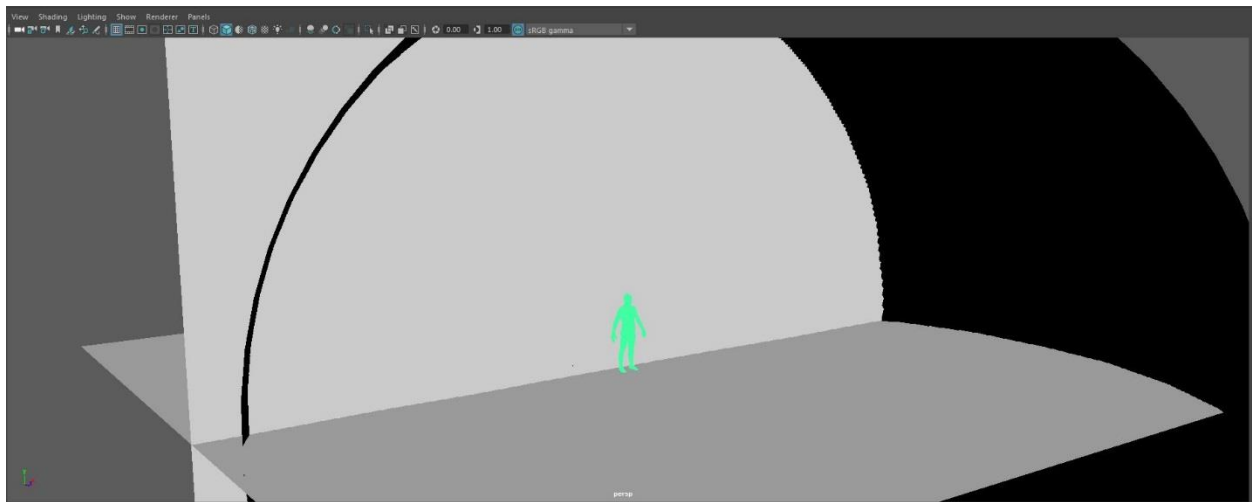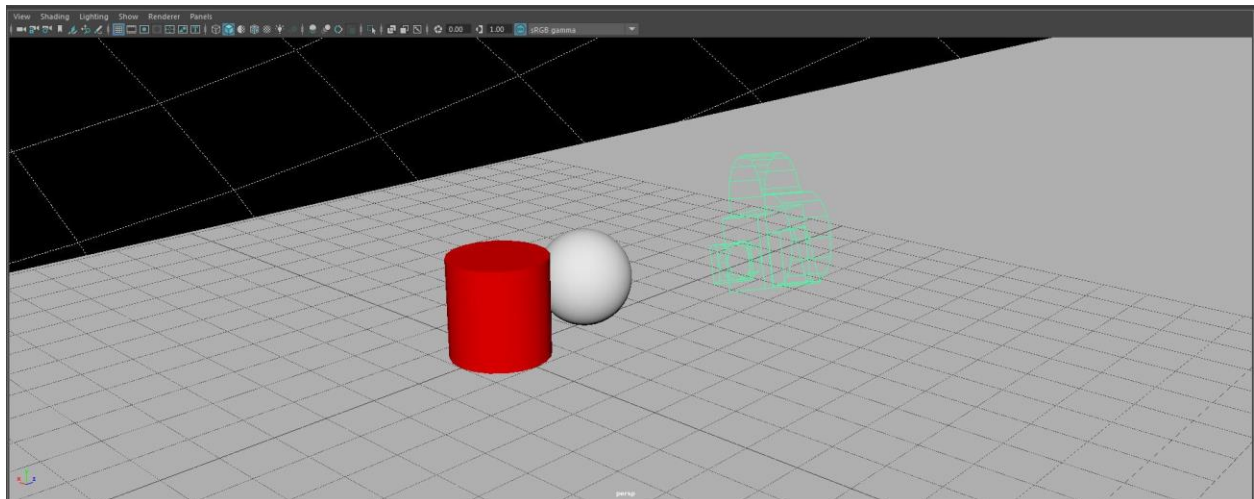
45_2) Paroptrical Colours
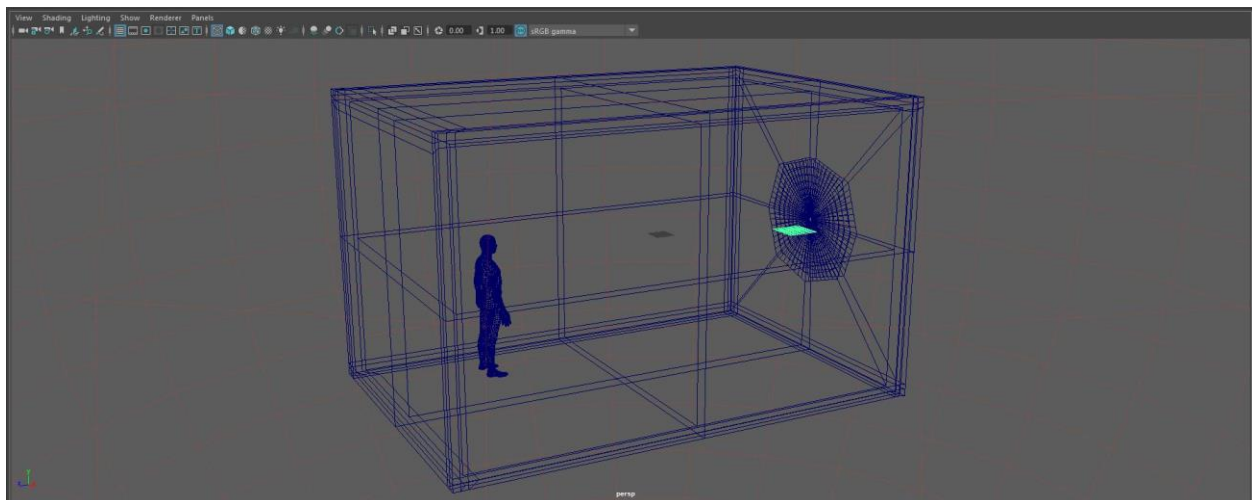
46_3) Paroptrical Colours

47_4) Paroptrical Colours

Augmentation of Colour (48-49)

50_1) Communication, Apparent