

HELIOCENTRIC ARCHITECTURE

Materializing Solar Cadences

by Trygve Wastvedt

Bachelor of Arts in Mathematics and Studio
Art
St. Olaf College, 2010

Submitted to the Department of Architecture
in partial fulfillment of the requirements for
the degree of Masters of Architecture at the
Massachusetts Institute of Technology.

February 2015

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Abstract

There is a long tradition of architecture creating atmospheric, awe-inspiring experiences by shaping and making visible natural light. Another similarly long-established approach to daylighting optimizes lighting conditions through the use of computational tools which provide precise numerical and geometric models of solar rhythms. This thesis applies the quantitative control of computational methods to the creation of atmospherically daylit architecture, making possible spaces whose form, tuned to the rhythms of changing daylight, reveals latent celestial cycles.

Traditional printed media afford limited potential for experiencing atmosphere. Thus, the thesis explores the use of video media and virtual reality to present an immersive experience of the architecture.

Thesis Supervisor

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More so than most, this thesis has relied on a milieu of recent technological developments not just for the production of images but for nearly every aspect of design, representation, and presentation. This has been made possible by a staggering multitude of people. Autodesk, Next Limit, Unreal, and Microsoft make powerful software and make that software available to students for free. David Rutten at McNeel created Grasshopper which I used for everything and which was literally essential for my design process. Andrew Hazelden and Roberto Ziche updated their GitHub page ten days before my final review, providing me with the tools I needed just in time. Laird Malamed at Oculus made sure I had more Oculus Rifts than I could handle for my final review.

Closer to home, I have benefited immensely from the supportive community of the MIT architecture department. I am particularly grateful for everyone who helped me in the

final end-of-semester push. Austin, Evan, Joel, Jongwon, Justin, Luisel, Maya, Maxwell, Rik, Ulises, and Zhao trusted me with loans of thousands of dollars worth of equipment for my final presentation. My tech team, especially Austin, Enas, Kim, Maya, and Zhao, set up all of that equipment and made the virtual reality happen. Enas, Luisel, Seto, and Tyler made drawings and models for me, working long hours on someone else's project in the middle of finals. You are my heroes. Christoph and Andrzej, my readers, gave insightful and actionable critique. And Joel Lamere, my adviser, has been my guide and coach for the past year. Thank you for your enthusiasm, trust, encouragement, and wisdom.

Finally, endless thanks are due my family and Kim, who kept me sane, stable, and well fed over the past three and a half years. I love you all.

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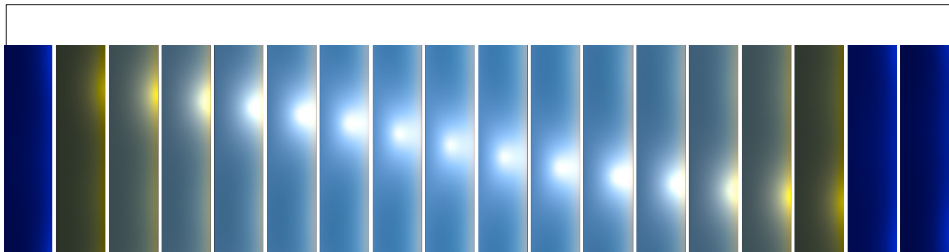
trygvewastvedt.com/heliocentric

For archiving purposes, MIT requires all theses to be submitted in book form. However, a thesis which investigates immersive representation cannot be fully represented in the medium from which it is trying to break away. While this document describes all parts of the thesis, please visit the website above for a complete representation of the thesis and an exploration of these new media.

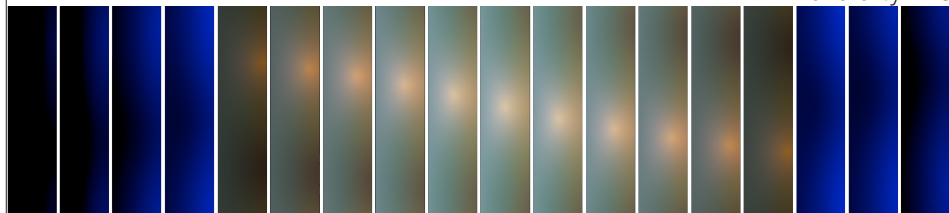
Heliocentric Architecture



1 | **Visible sunlight** Tadao Ando - Church of the Light, Japan

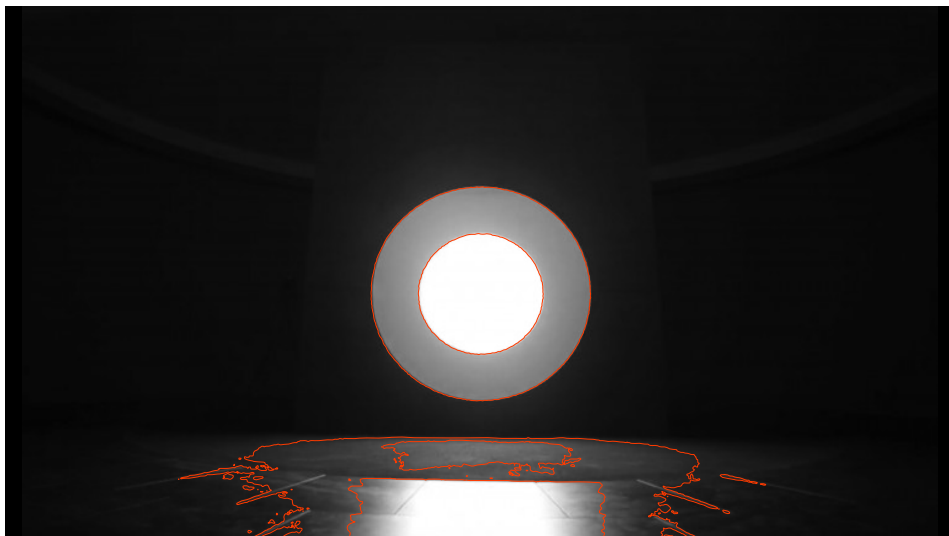


Turbidity: 2.5



Turbidity: 12

2 | **Atmospheric algorithms** Rendering the sky



3 | **Atmospheric sunlight** James Turrell - Roden Crater, Arizona

INTRODUCTION

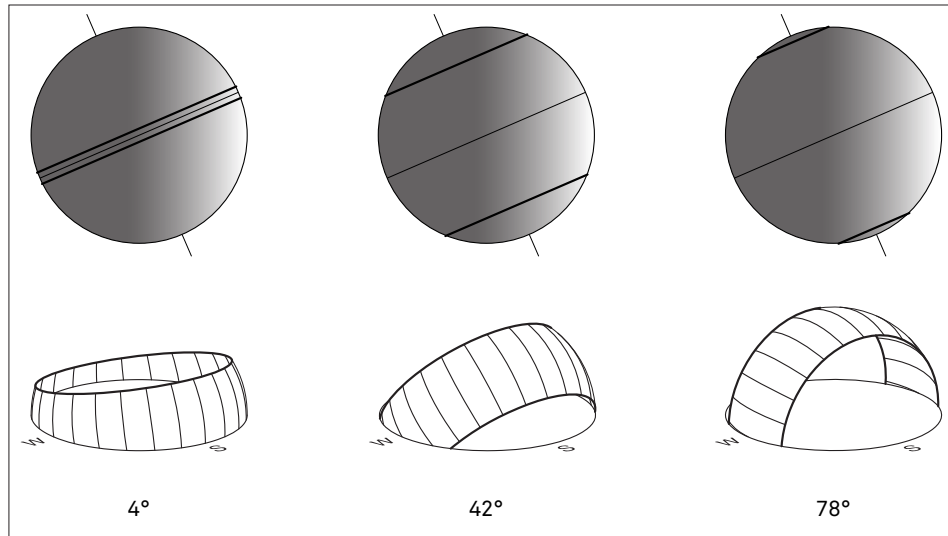
There is a long tradition of architecture which creates atmospheric, awe-inspiring experiences by shaping and making visible natural light within a space. For example, the front window in Tadao Ando's Church of the Light in Japan shapes the sunlight entering the space into a defined figure (Fig. 1). In addition to illuminating its surroundings, the light inhabits the space with a body given it by the architecture. A similar strategy and effect is seen in buildings such as the Pantheon or the work of Steven Holl. In these spaces the building makes sunlight visible by forming it into distinguishable figures. The presence of these figures gives sunlight an identity in the space and can create a sense of wonder or awe.

An alternative approach to daylighting seeks to optimize lighting conditions through the use of computational tools which provide precise numerical and geometric models of solar rhythms. For example the Villa Girasole, by Angelo Invernizzi, physically rotates about a central axis in order to maximize the amount of direct sunlight inside the house. Less dynamically, devices such as sun shades, louvers, and awnings are driven by computational models to maximize the amount of sunlight, reduce glare, or optimize the evenness of light in a space.

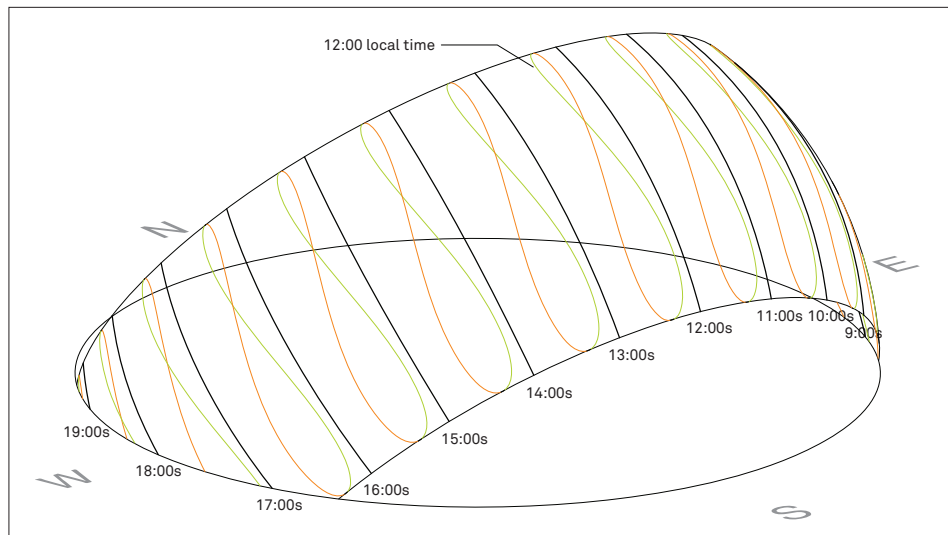
This thesis expands the computational and geometric models typically used for optimization to the analysis and generation of atmosphere. For example, the colors of the sky and the sun are quantities which can be measured, modeled, and simulated. As shown in Figure 2, a numerical model of the relationship between the color of the sky, the position of the sun, and the quality of the atmosphere can be used to simulate the sky's appearance.

One example of a similar undertaking is James Turrell's Rodin Crater in Arizona. The project is an observatory for a variety of celestial phenomena, where each part of the structure is tuned to a particular event or effect. For example, the 260 meter long Alpha Tunnel focuses the setting sun on the winter solstice onto a stone slab, creating a space which is occupied and defined by sunlight (Fig. 3). Turrell's tunnel is activated once a year, when the setting sun aligns with the tunnel's axis. This thesis explores the possibilities of an architecture which is daily in tune with the sun, continuously materializing solar cadences.

Heliocentric Architecture



4 | **Solar swath**



5 | **Apparent solar time**



6 | **Virtual reality** Oculus Rift DK2

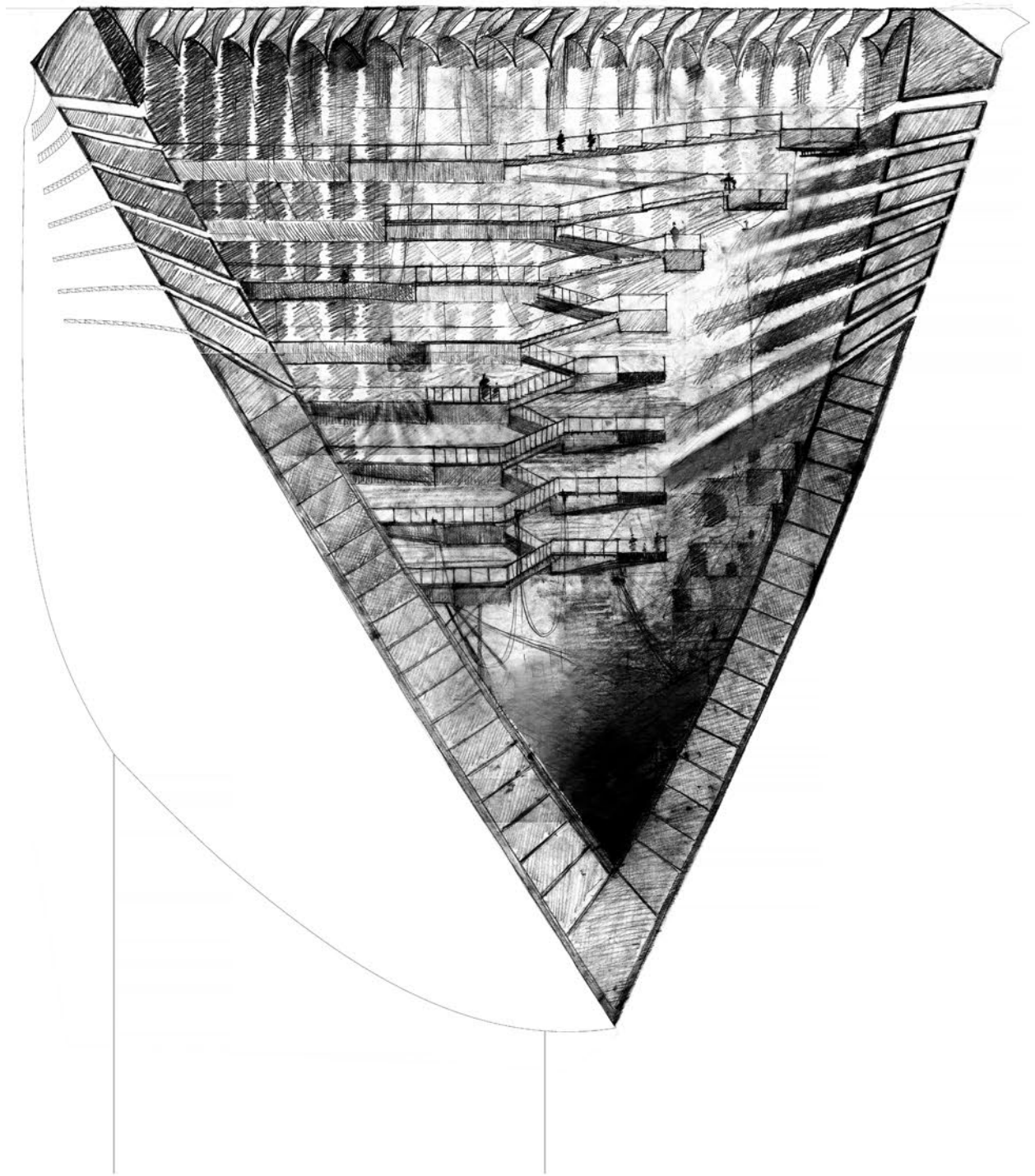
For the purposes of this exploration the complexities of an architectural site have been reduced to a single number: latitude. A site's latitude is its only characteristic which has a significant effect on the position of the sun in the sky. The latitude of the site determines the swath of the sky covered by the sun over the course of the year as well as the shape of the sun's path through the sky relative to the horizon (Fig. 4). At latitudes close to the equator the solar swath forms a nearly vertical band from east to west. The sun appears to traverse a line which passes nearly directly overhead and shifts north to south depending on the time of year. At latitudes close to the poles the solar swath forms a band nearly parallel to the horizon and the sun travels in a circle at an altitude which varies depending on the time of year.

The position of the sun in the sky can be roughly calculated given three quantities: the site's latitude, the day of the year, and the time of day. (A precise calculation involves a number of other factors - see Appendix 1 for details.) The third of these, the time of day, presents some noteworthy complications. We have but recently imposed a metric for recording the time of day which trades some degree of geometric regularity for temporal regularity. In order to standardize a day to a constant 24 hours the sun's position in the sky at a given time varies throughout the year. As shown in Figure 5, for a particular hour of the day the sun's position moves through a curve, called an analemma, over the course of the year. Furthermore the construct of time zones, only a century old, allows the coordination of time between different longitudes but causes these analemmas to shift east and west based on one's longitude.

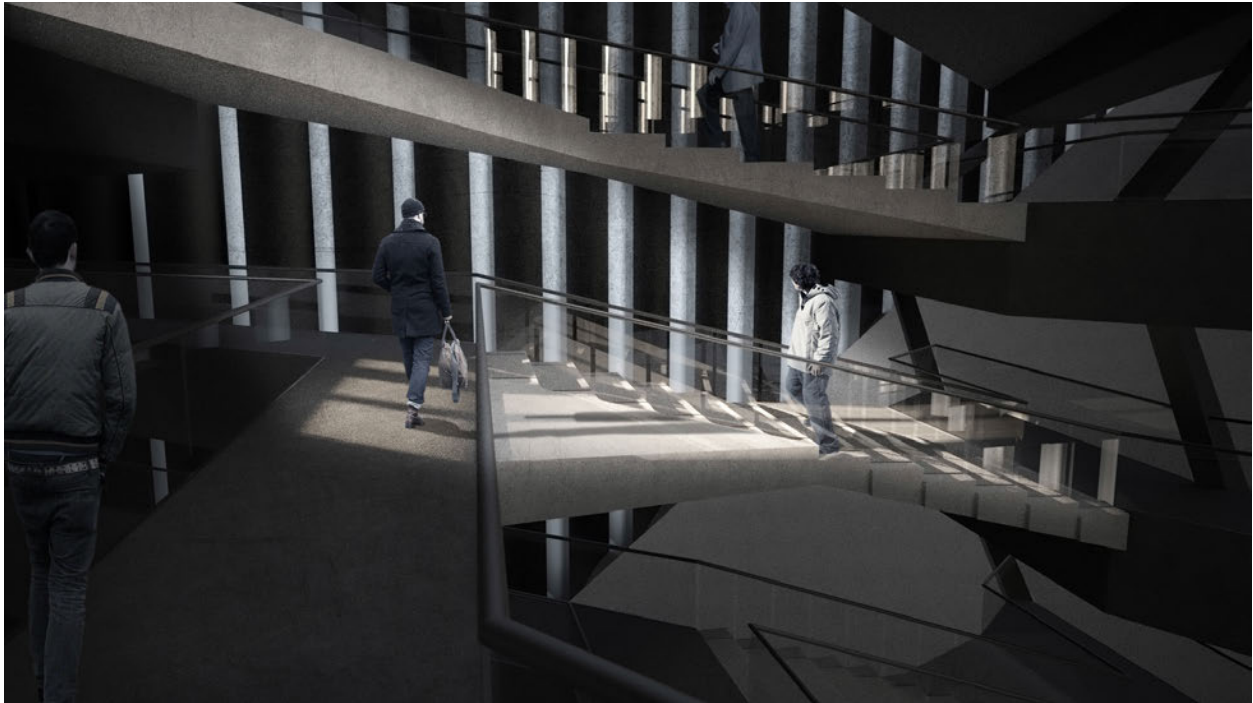
Before mechanical clocks became common, a city's time was set solely by the movement of the sun each day. This thesis returns to the metric of apparent solar time, which is more directly connected with solar rhythms. Noon occurs when the sun is positioned due south, regardless of the time of year.

Both printed and screen-based media are inherently limited in their ability to represent the atmosphere created by visible sunlight. This thesis explores the use of virtual reality as an alternative means of representation which creates immersion and presence, allowing atmosphere to be felt and experienced. In particular, the representation of the thesis was developed using the Oculus Rift headset (Fig. 6). The headset is simply a bright, high definition screen enclosed by a shell which eliminates visual distraction. Each eye sees a slightly different image which creates a stereoscopic effect simulating a three-dimensional environment. In addition, sensors track motion and orientation allowing the display to change as the user turns their head. The isolation, radiant lighting, stereoscopic effect, and interactivity combine to create an immersive experience which communicates the feeling of being in a space.

The computational methods to describe the sun's position and to control geometry in relation to its movement can be employed in a variety of ways to create atmospherically daylit spaces. In addition, the latitude of a site affects the sun's movement and thus provides varying affordances to this solar tuning. What follows are three buildings at a range of latitudes, each of which takes advantage of the particularities of its location to create a unique relationship with the sun. At 4 degrees latitude, a spiral stair connects two high-rise towers. The surfaces in the building capture sunlight at the same specific moments every day, emphasizing the movement of the sun. At 42 degrees latitude, a rare books library features a subterranean reading room. The floor plates of the library filter sunlight to emphasize movement and to prevent the sun from shining on the rare books. Finally, at 78 degrees latitude, a monumental structure focuses the sun into a line of light which occupies the same space and trajectory as people. Both occupants (solar and human) are juxtaposed onto the same circular path.



7 | **Section** (Rendering: Erioseto Hendranata)



8 | 17:00s (Photoshop: Luisel Zayas)

Over the course of a day the changing position of the sun causes the patches of sunlight cast by windows to move through a space. Though the space may be designed with this in mind, to collect morning light or to shade from the hot afternoon sun, any such alignment is typically approximate and general. In 4°, the form of the building is precisely aligned to the movement of the sun so that over the course of a day the sun follows an inscribed path through the space.

4° is an interstitial atrium linking two high-rise buildings. A spiral stair rises through the

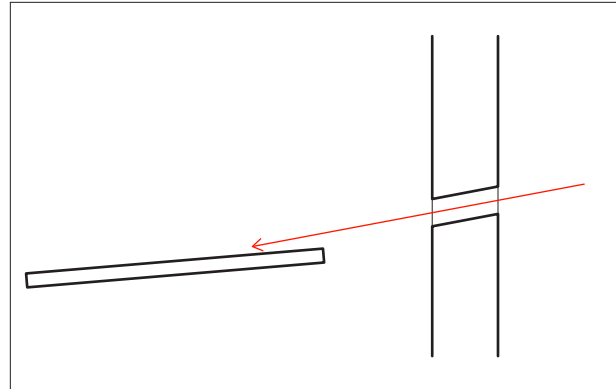
center and connects the floors of each building with each other. The stair planes and the walls are aligned so that direct sunlight in the building follows a similar path each day, illuminating the same series of surfaces. On the stair planes the sunlight dramatically occupies the same surface as the people, elongating the shadows cast by occupants. The raking angle of the light also causes the patches of sunlight to move rapidly over the stairs, making the movement of the sun nearly perceptible to occupants.

Method

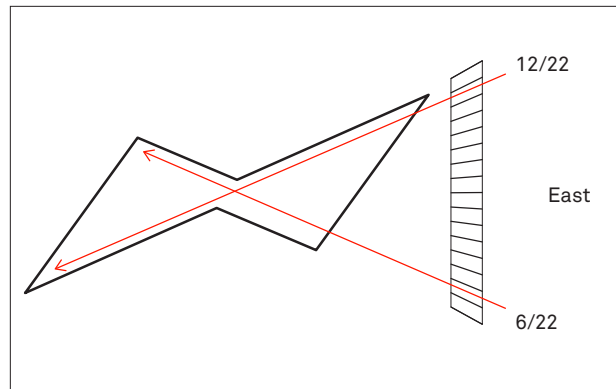
When the sun shines through a window into a space it typically creates a pool of light on a wall or floor of roughly the same dimensions as the window. In order to illuminate a larger area of the building, a larger window is typically required. If, however, the sunlight encounters a surface angled at nearly the same inclination as the sun rays, a very small window can illuminate a very large surface area. This enables the building to closely control the sunlight with small windows while still creating a dramatic effect inside.

The basic device of the interstitial space at 4° is a series of narrow but deep window slits which only allow light into the space during a brief period of the day. The slit of light coming through the window is then cast onto a plane inclined slightly relative to the direction of light so that the sunlight occupies a large surface within the building (Fig. 9). Each window is tuned to a particular time of day but allows light in at that time of day on every day of the year. To accomplish this each window is lengthened into a strip and a series of baffles are inserted. The baffles ensure that light at a given angle only enters through a short section of the window. The planes are correspondingly shaped to display a long swath of light for the full annual range of light angles (Fig. 10).

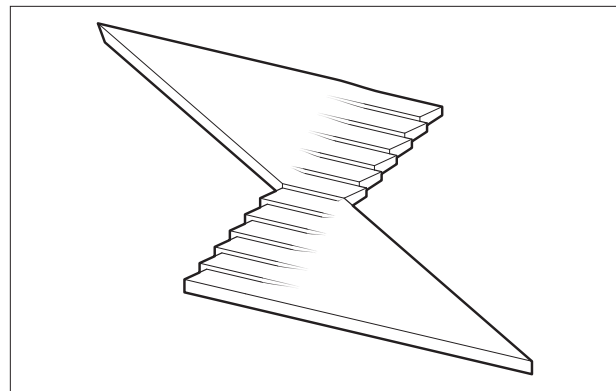
Because of the slight angle between plane and sunlight, the sunlight moves relatively quickly across each plane. The sun takes approximately 20 minutes to pass entirely across a plane, during which time the full length of the plane is illuminated for only a couple minutes.



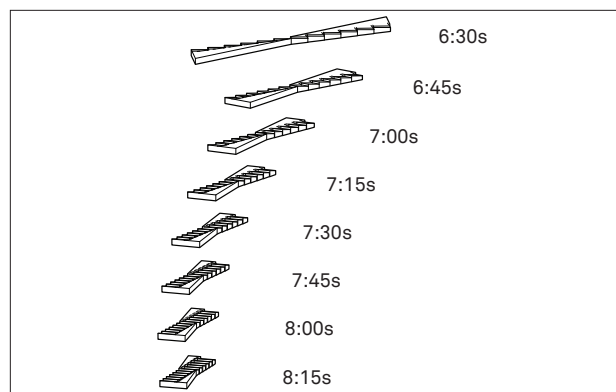
9 | **Stair plane sun filter** diurnal control



10 | **Stair plane sun filter** seasonal control



11 | **Stair plane**



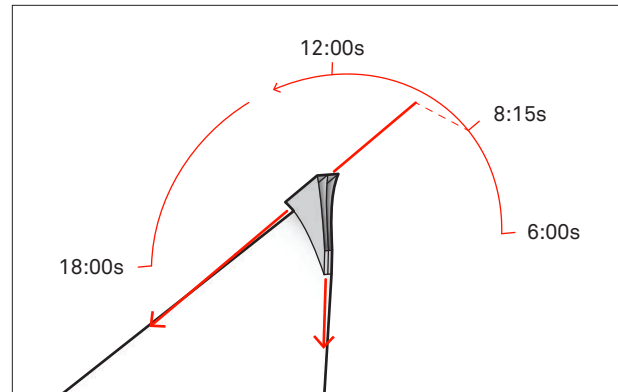
12 | **Spiral solar stair**

Thus a series of planes, each inclined differently, capture sunlight every 15 minutes as the sun rises in the sky. A stair is cut into each of the planes to allow people to occupy the same space as the sun (Fig. 11). These planes form one half of the spiral stair (Fig. 12).

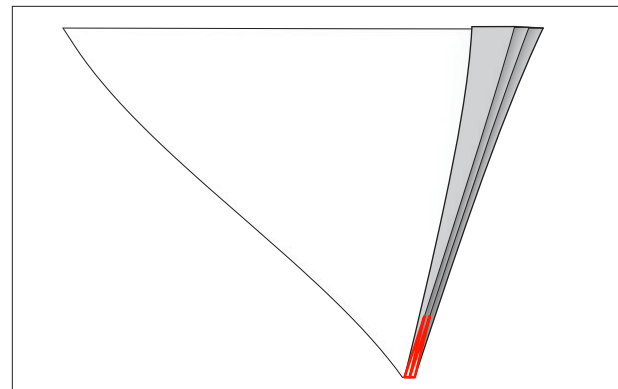
After 8:15 solar time the altitude of the sun in the sky causes the corresponding plane angle to be too steep to accommodate a stair. Instead, the sunlight is filtered in through a linear skylight in the roof and strikes the side wall (Fig. 13). The skylight is twisted so that light at a given angle can only enter along a short segment of the skylight's length (Fig. 14). A single baffle running the full length of the skylight further limits the width of the swath of light allowed through. As the sun rises the sunlight traces a vertical line on the wall which takes four hours to move the length of the space. At noon, because of the site's low latitude, the sun is nearly directly overhead and thus the wall is nearly vertical, meeting up with the neighboring building.

In the afternoon the illumination sequence is reversed - the sun traces a line which moves along the western wall until 3:45 solar time at which point the angle of light is again amenable to a stair and illuminates the second half of the planes in the spiral stair until sunset (Fig. 15).

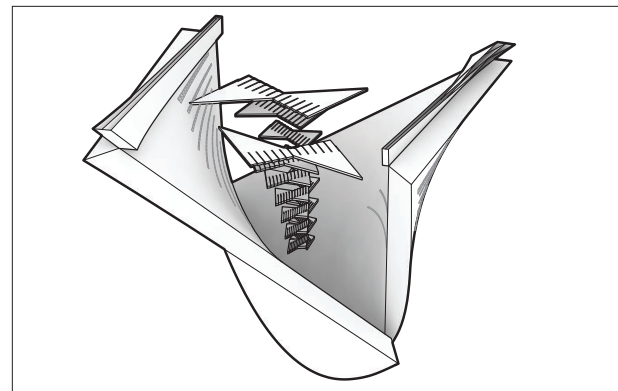
Because all of the openings are tightly controlled in order to only let in light at precise moments, the level of ambient illumination in the space is very low. In order to make the space more usable for people, the remaining walls and the roof allow ambient daylight to illuminate the space. These surfaces are constructed from a series of light scoops which collect indirect light from the sky and from bouncing sunlight while blocking all direct light (Fig. 16).



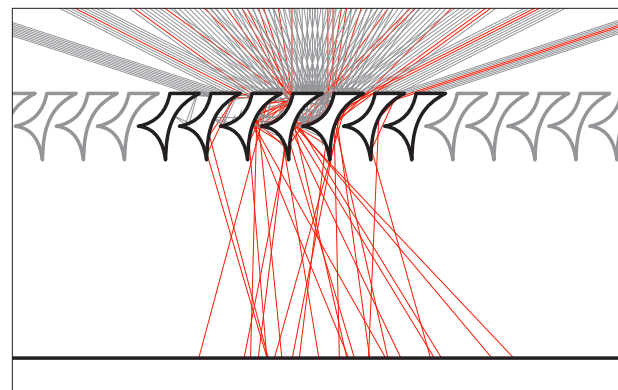
13 | **Skylight sun filter** diurnal control



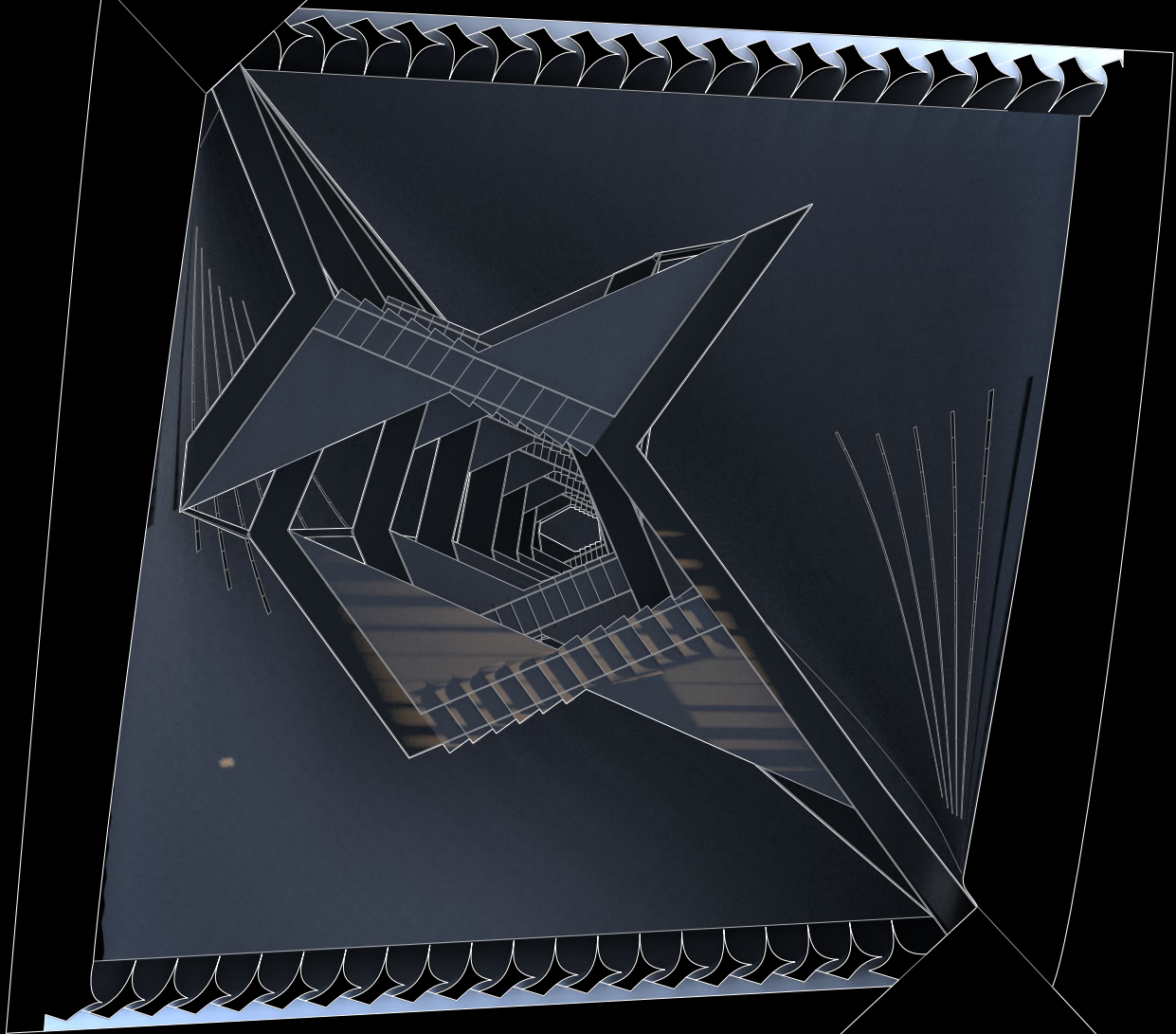
14 | **Skylight sun filter** sun's perspective at noon



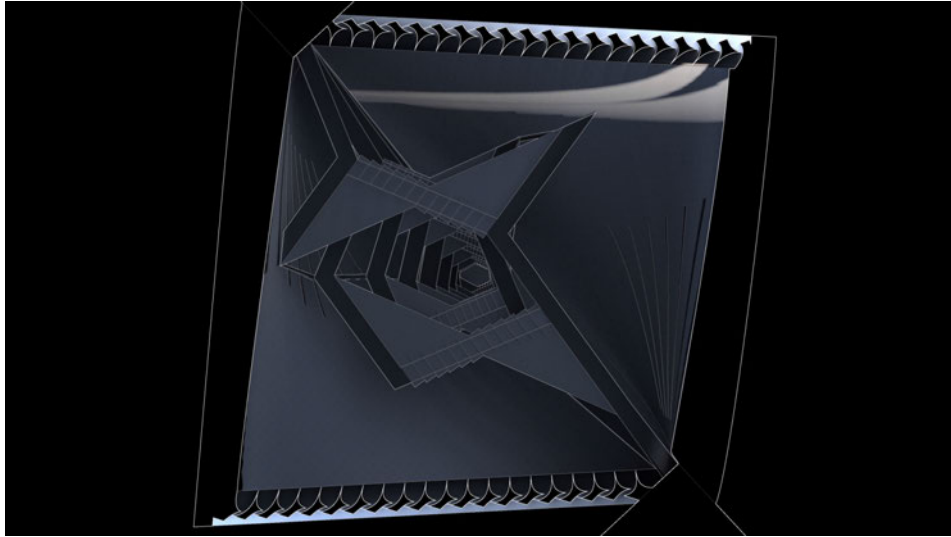
15 | **Active surfaces**



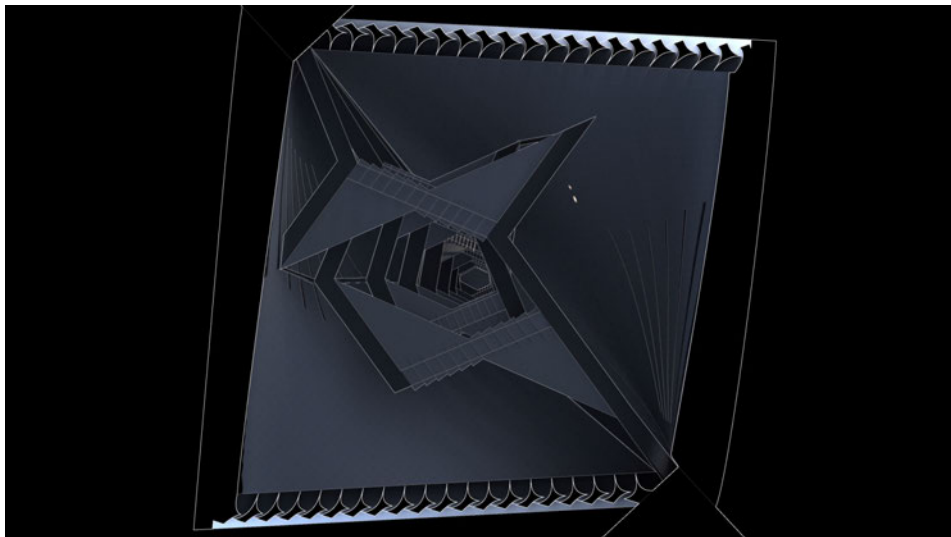
16 | **Light scoops**



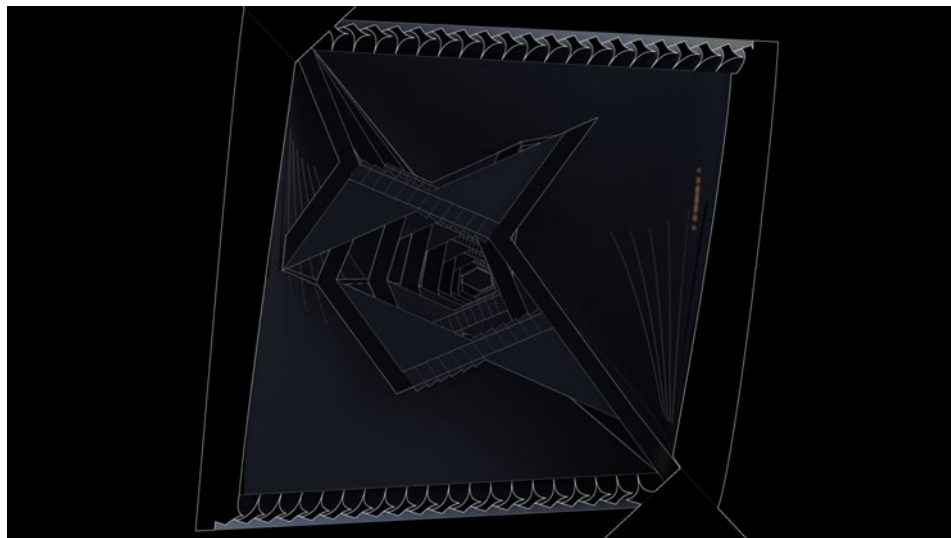
4°



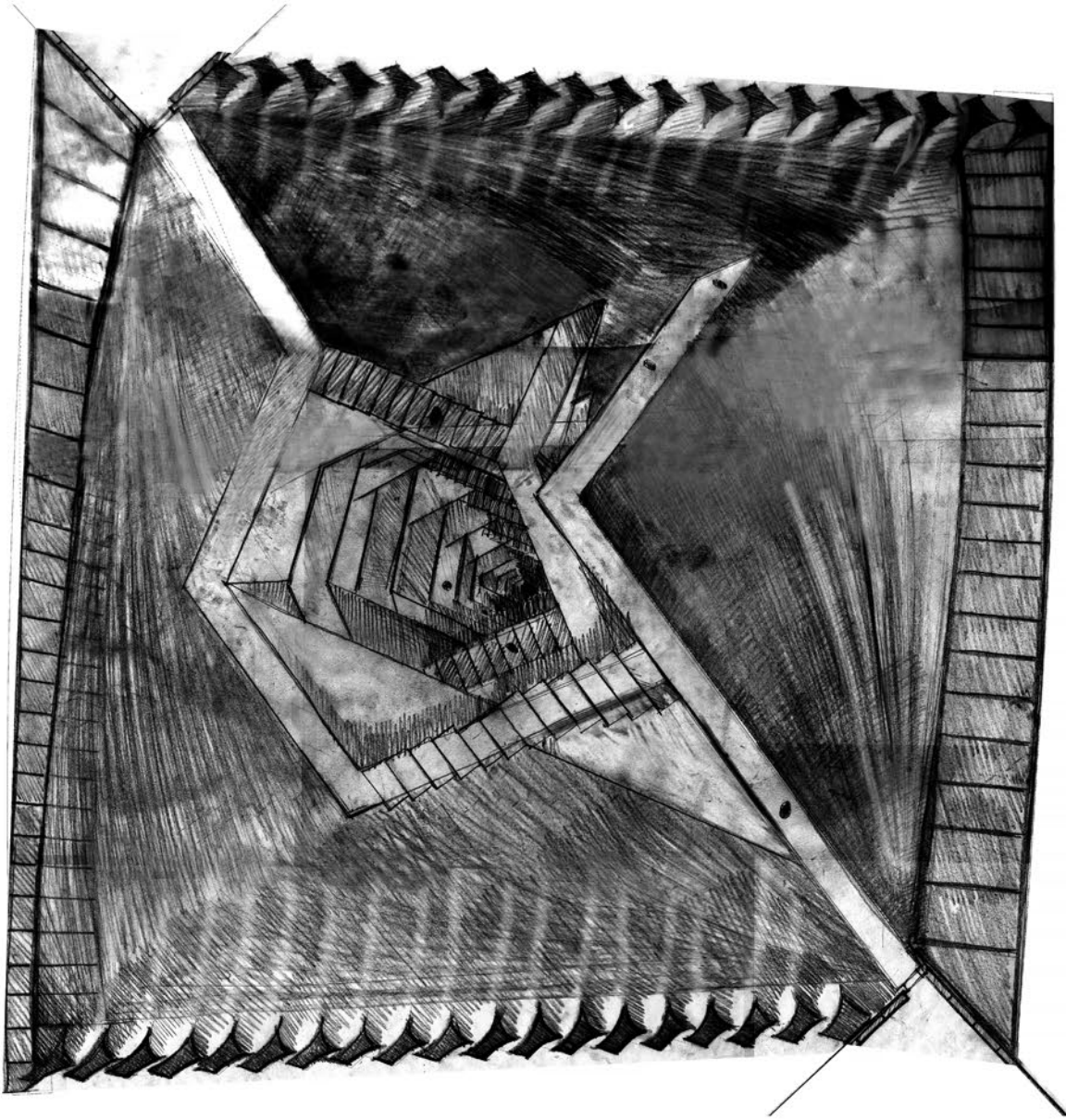
18 | **6/22 11:00 s** (frame from animation)



19 | **6/22 16:45 s** (frame from animation)



20 | **6/22 18:00 s** (frame from animation)



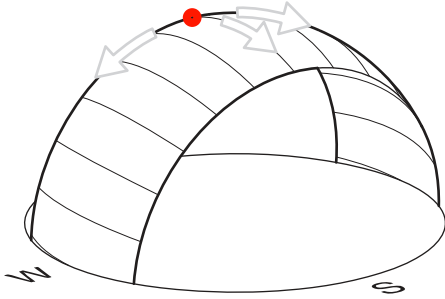
21 | **Plan** (Rendering: Erioseto Hendranata)

The drawn representation of 4° is rendered in the style of Giovanni Battista Piranesi (above and on page 12). Piranesi's *Carceri* (Prisons) etchings use dramatic lighting to create depth and volume and to accentuate the labyrinthine nature of the architecture. Though the spiral stair in 4° is a simple path, not a maze, the space is a network of stairs and bridges which particularly in section bears a resemblance to Piranesi's prisons.

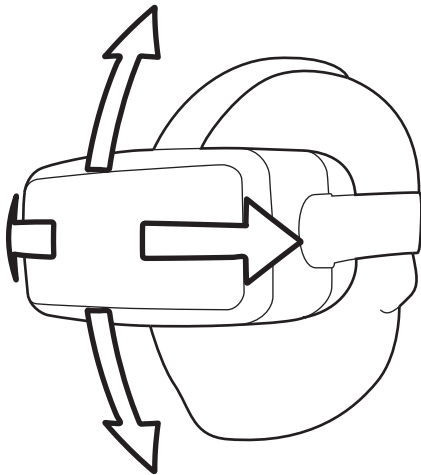
4°



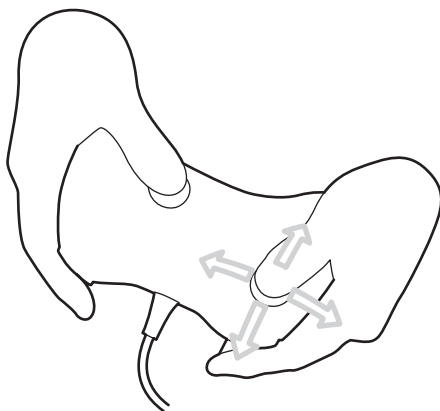
22 | 3D printed model



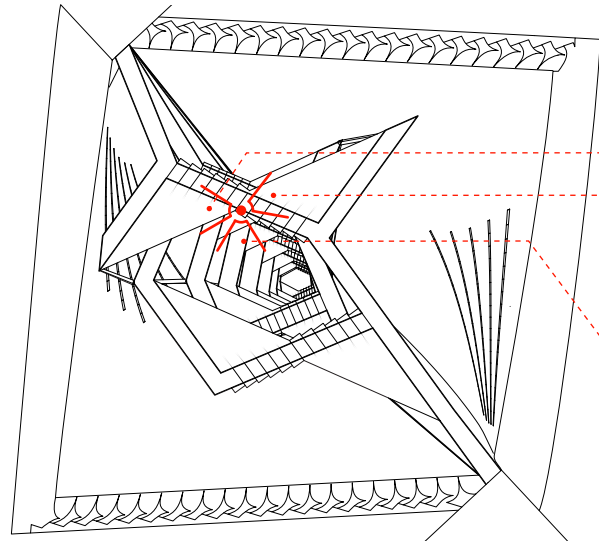
No change in time



Can control view direction



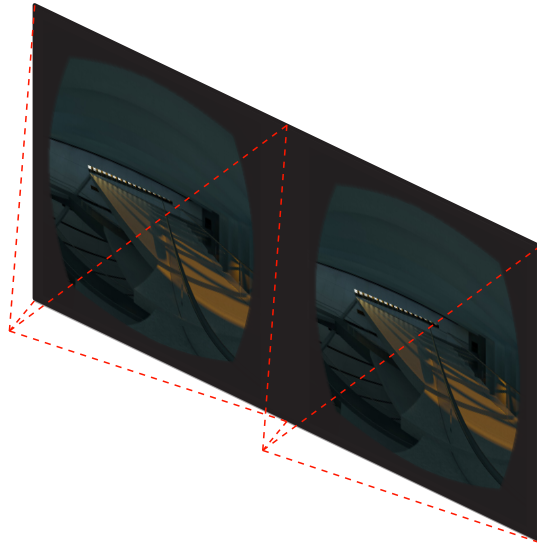
No movement



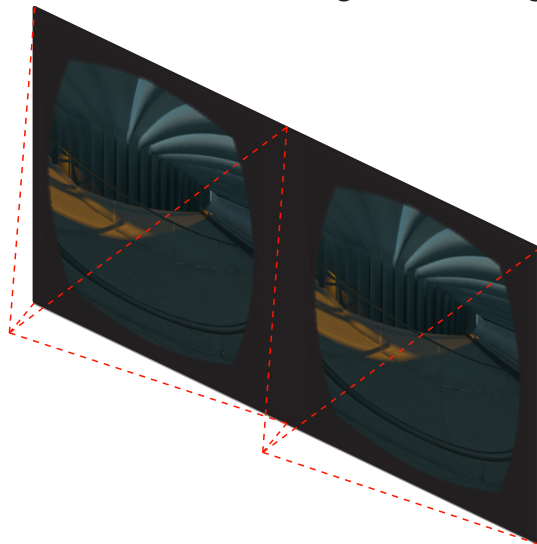
The virtual reality experience for 4° limits a number of potential interactions in order to allow for a higher quality rendering. The point of view is fixed and the point in time is fixed, but the viewer can turn their head to look around them in all directions. The content is similar to a conventional digital rendering but with a horizontal field of view of 360° and a vertical field of view of 180° so that all possible view angles are rendered. The rendering is also calculated twice, at slightly different locations. When viewed in virtual reality each eye sees one of the renderings, creating a calibrated stereoscopic effect that mimics that of natural vision.

As the viewer rotates their head, the view shown on the display changes to show different parts of the space. The rendering places the viewer in the middle of the top stair at the inside edge, as if they were leaning out over the railing (Fig. 23). The time is set (17:30s) so that the entire length of the top stair is illuminated with a swath of sunlight which passes right next to the viewer (Fig. 24). Above and to both sides the light scoops in the walls and ceiling are visible (Fig. 25).

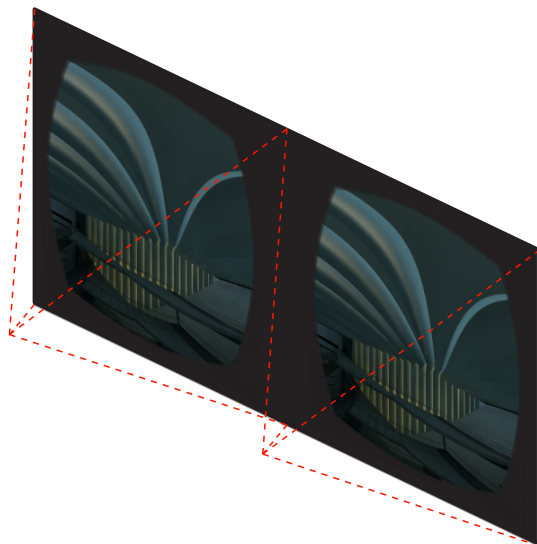
4°



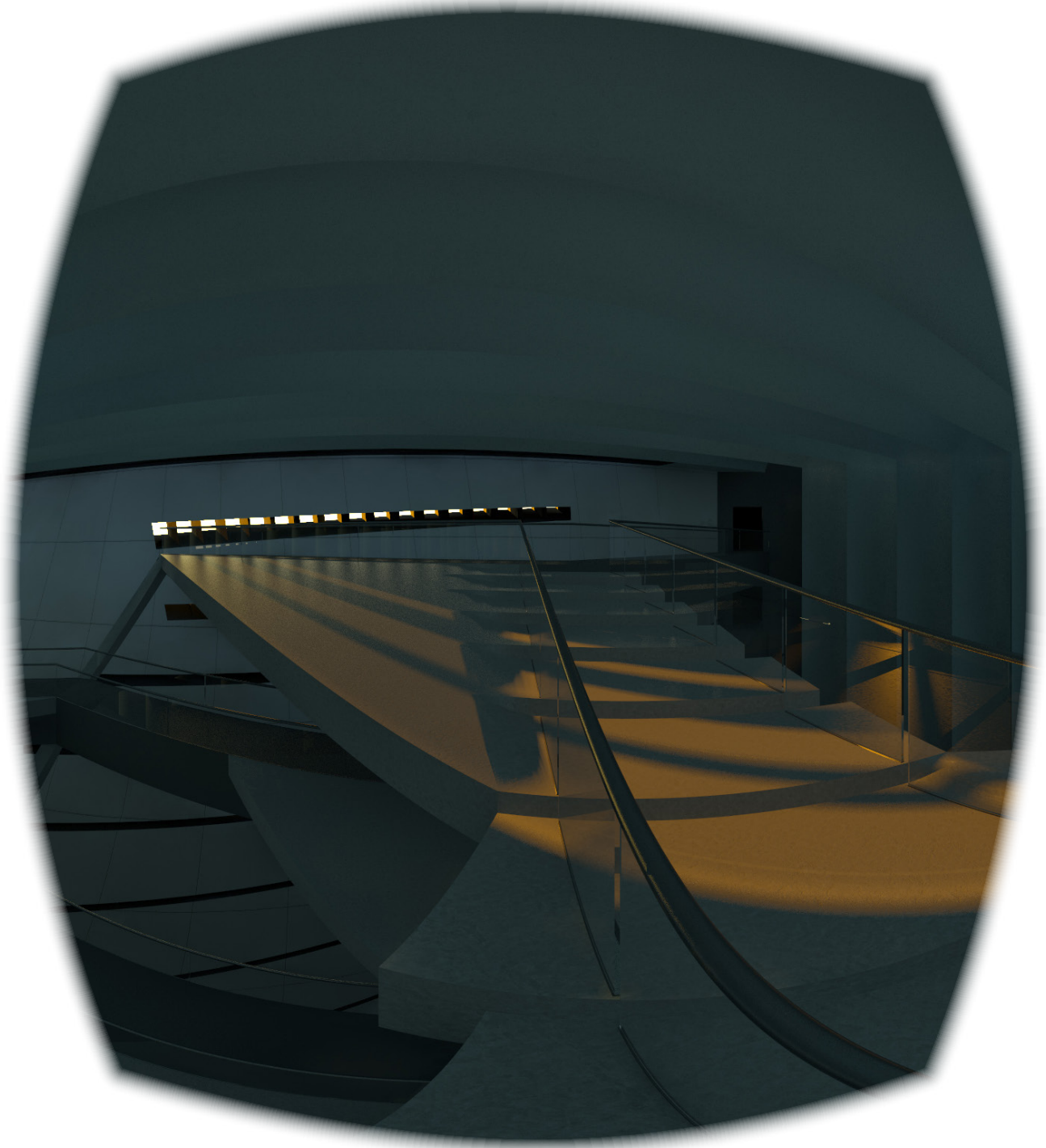
23 | **Leaning over the railing**



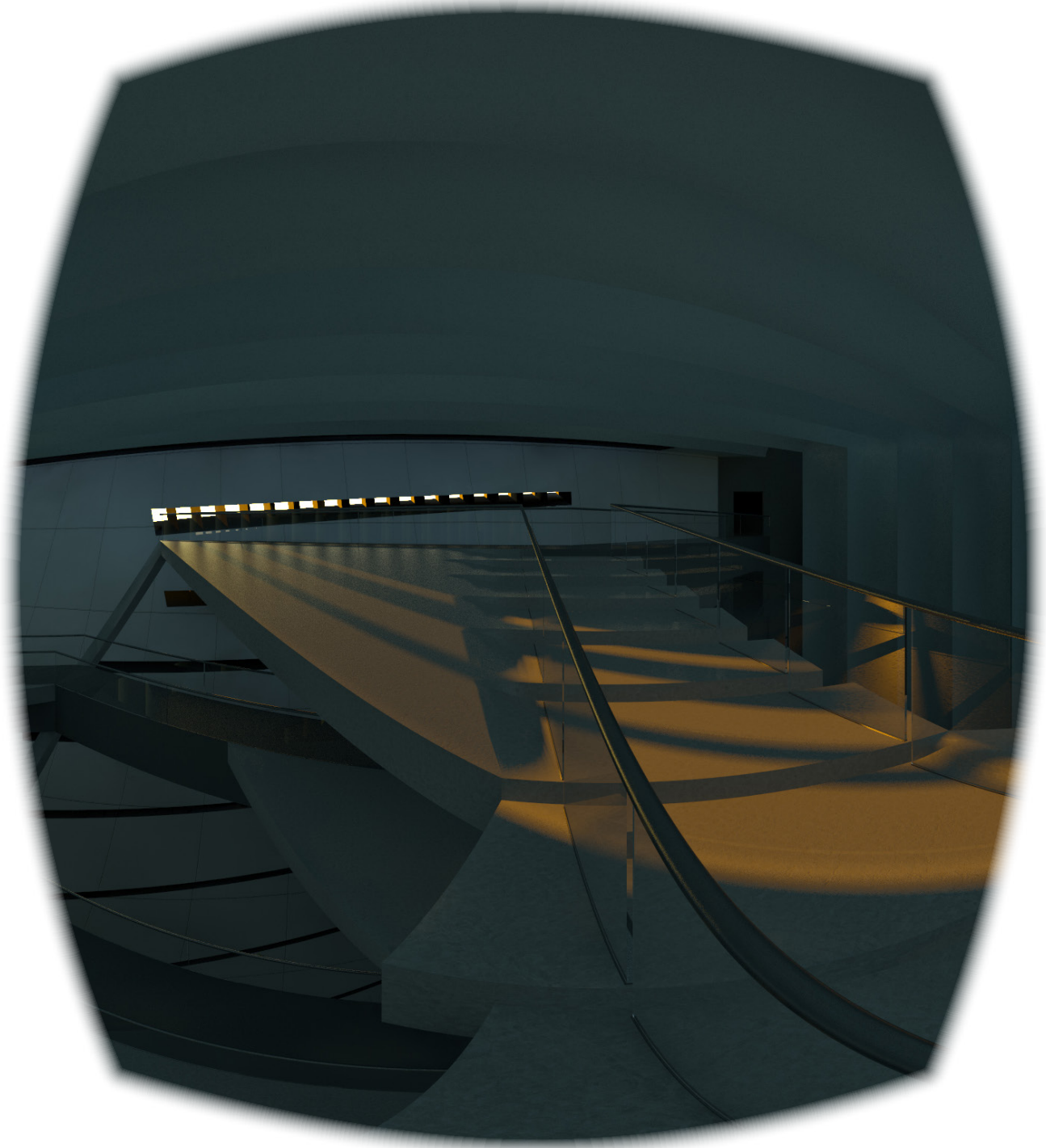
24 | **Swath of sunlight**



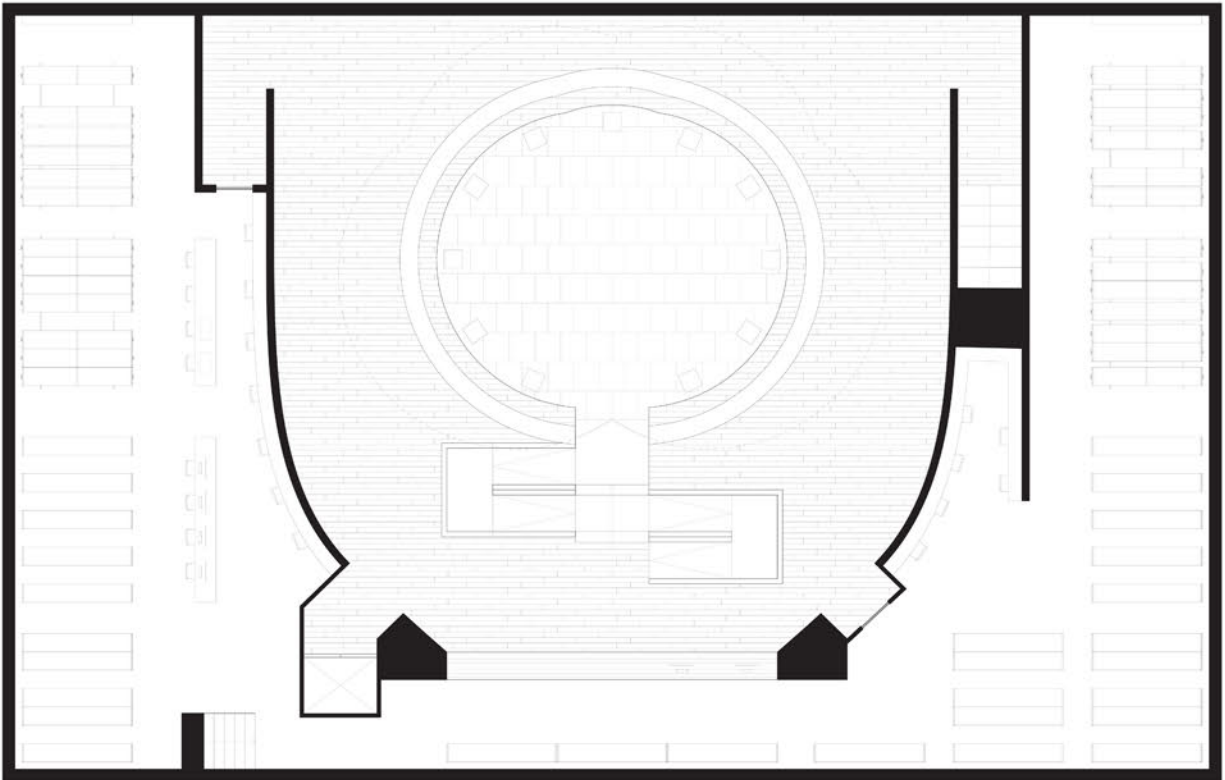
25 | **Light scoops**

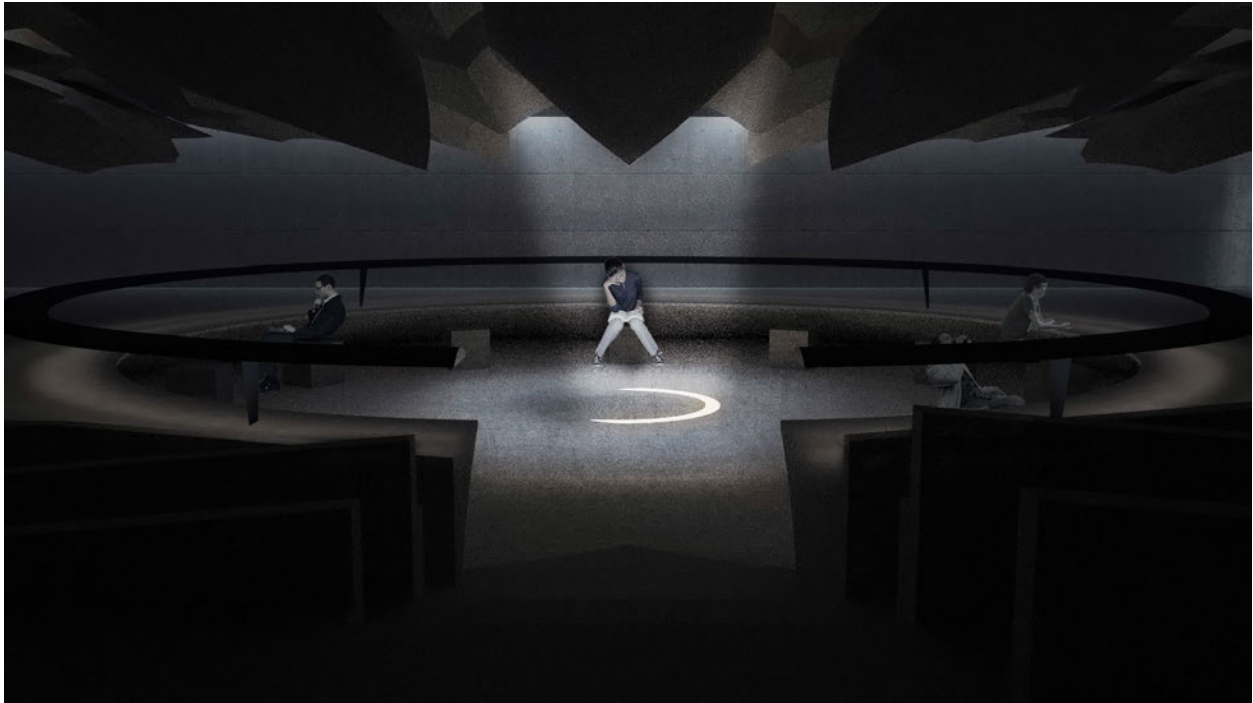


4°



26 | 12/22 17:30s Virtual reality





28 | 3/23 11:00s (Photoshop: Luisel Zayas)

42° is designed as a rare books library. In order for a library to house rare, old, or otherwise delicate material, the room in which the books are kept and read must be carefully protected from a number of potential hazards. Most notably, direct solar radiation on printed material causes the ink to fade and the paper and bindings to deteriorate. Consequently rare books are typically housed in rooms without any windows.

The rare books room at 42° is tuned to allow in carefully controlled direct sunlight which

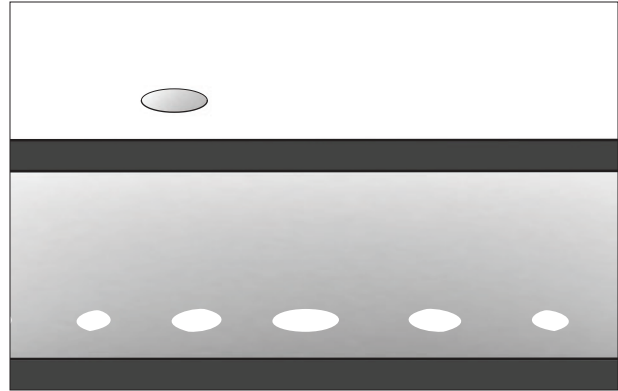
never falls on surfaces which might hold a book. People studying in the space enjoy the presence of natural light while the delicate material remains safe from UV radiation. The books are housed in a subterranean space underneath the ground level of the library. The ceiling and floor of the ground level, as well as the furniture, act as filters which control when and where sunlight can shine into the reading room. In the reading room a series of arcs of light traverse across the floor, creating a different pattern each day of the year.

Method

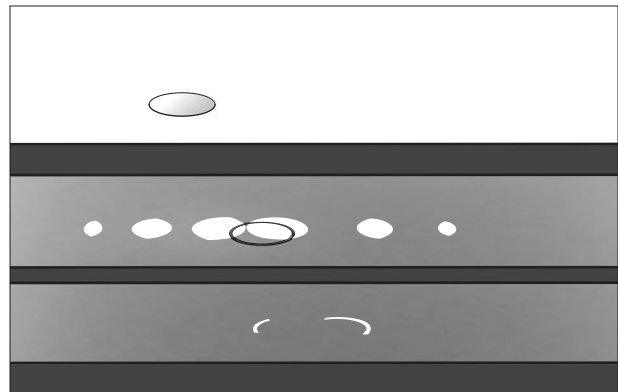
The sunlight shining into the reading room is filtered through openings in the two ceilings above. The first filter is the roof of the ground floor, in which is carved a series of circular skylights. Over the course of a day one of these skylights traces a disk of sunlight on the basement floor which moves from west to east over a large area (Fig. 29). Because the skylight admits light from very low angles, the distance the sunlight travels across the floor is too large for the reading room.

To limit the area covered, a second filter is imposed at ground level. At this level a ring of glass is embedded in the floor. The second filter catches most of the extreme angles of sun that pass through the top skylight. However, when the sun is in the right position to shine through both openings an arc is traced out on the basement floor (Fig. 30). The sun is only aligned with both skylights during a short period of the day and thus the trace on the basement floor occupies a limited area.

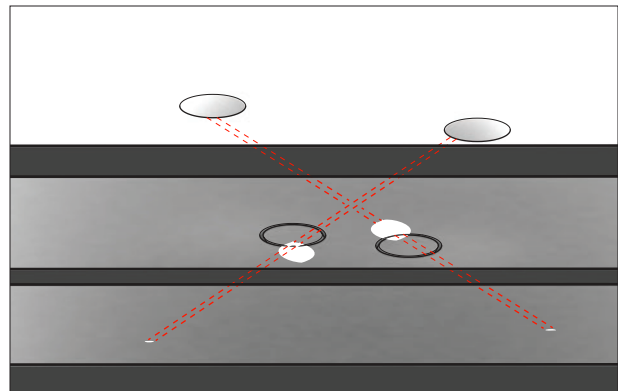
In order to always have direct light in the basement these filter pairs are arrayed across the ceiling and floor. However, this leads to problems when light from one skylight is able to pass through an adjacent ring, casting light beyond the reading well (Fig. 31). The furniture in the first floor is designed to block these unwanted angles. Benches form rings around the floor skylights and are open in the center to allow the cylinder of desired light through (Fig. 32). The benches are positioned to block all possible angles where sunlight could shine into a neighboring skylight pair. In addition to



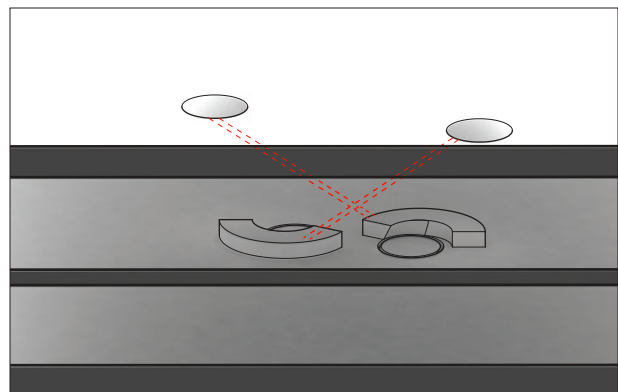
29 | **Single sun filter with circular opening**



30 | **Second filter and ring opening**



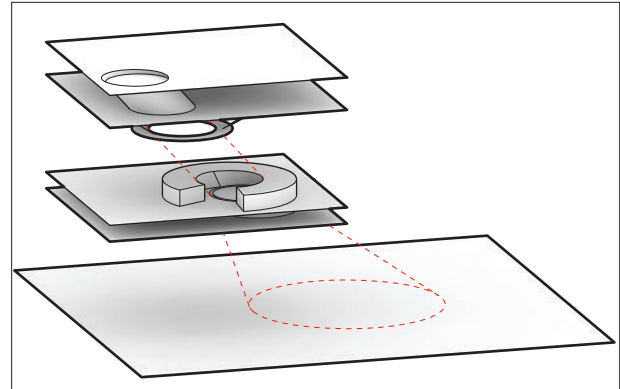
31 | **Errant light paths**



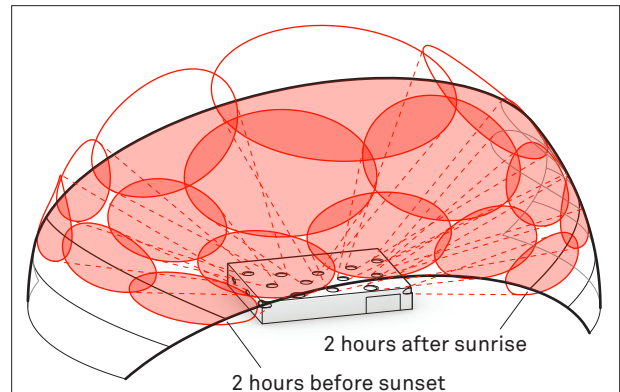
32 | **Benches block errant light**

the benches, circular lighting fixtures hanging in the ground level also help to block unwanted light angles.

An aligned set consisting of a circular skylight, lighting fixture, bench, and ring skylight creates a filter which projects an arc of sunlight onto a circular area on the basement floor (Fig. 33). In order to project light onto the basement floor at all times of the year, eighteen of these sets are arrayed through the building. Each set points to the same center point on the basement floor, but is angled differently to catch the sun at a particular time. The sets are distributed so that together they cover as much of the solar swath as possible (Fig. 34). The reading room is open on a schedule based on solar time, from two hours after sunrise to two hours before sunset. During that time at least one filter set is projecting light onto the reading room floor at all times, so that sunlight occupies the space whenever people occupy the space.

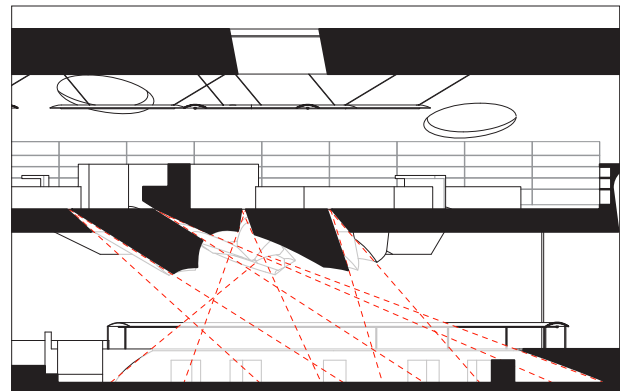


33 | Filter set



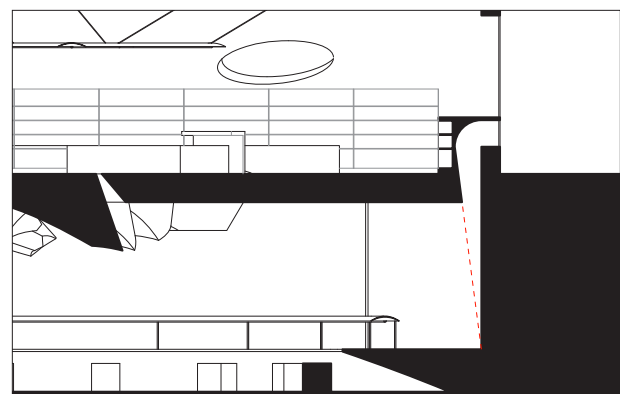
34 | Solar swath coverage

A reading well is recessed into the floor of the reading room. The shape of the reading well follows the outer limits of the traces of the filtered sunlight, so that the entire floor of the well is illuminated at some point of the year (Fig. 35). Patrons sit on chairs around the edge of the well and reading material can be safely placed on the desk, level with the floor of the rest of the room.



35 | Sunlight curves out the reading well

After hours the glow of diffuse daylight through the filters and a light scoop in the north wall continues to illuminate the reading room. (See rendering on page 28.) The light scoop prevents direct sunlight from entering the space and reflects daylight onto the back wall of the reading room (Fig. 36).



36 | Back wall light scoop



42°



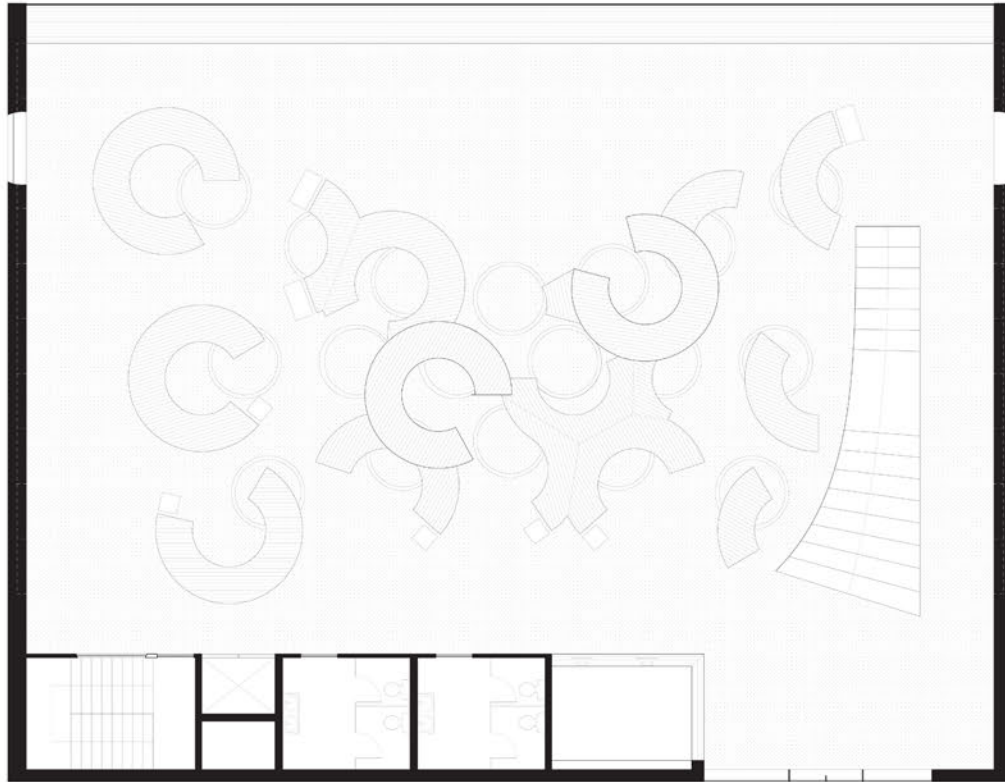
38 | **5/27 6:18s** (frame from animation)



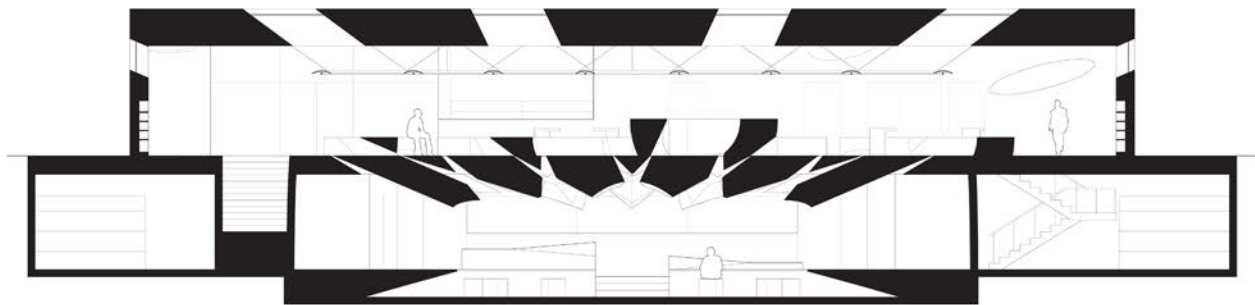
39 | **5/27 8:03s** (frame from animation)



40 | **5/27 15:20s** (frame from animation)



41 | **Plan** (Drawing: Erioseito Hendranata)



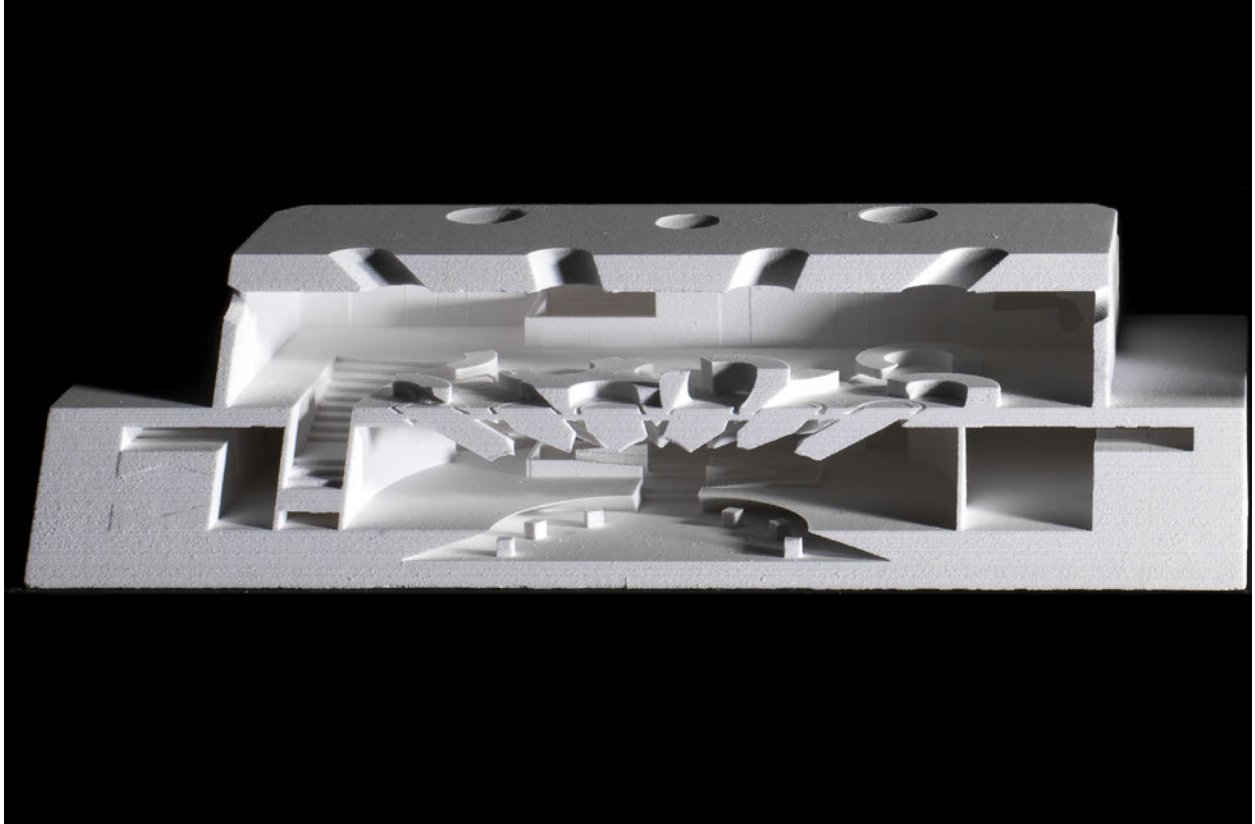
42 | **Section** (Drawing: Erioseito Hendranata)

42° borrows several motifs from the work of Louis Kahn. The material palette of the library imitates the materials of Kahn's Exeter Library: the walls are concrete, the floors and furniture are wood, and the featured spaces - at 42° the reading well - are paved in travertine marble. 42° also shares with much of Kahn's work a focus on primitive geometric figures like the circle. Most notably the circle is a prominent figure in Kahn's House of Parliament in Bangladesh as well as in the Exeter Library. Finally, while the methods employed

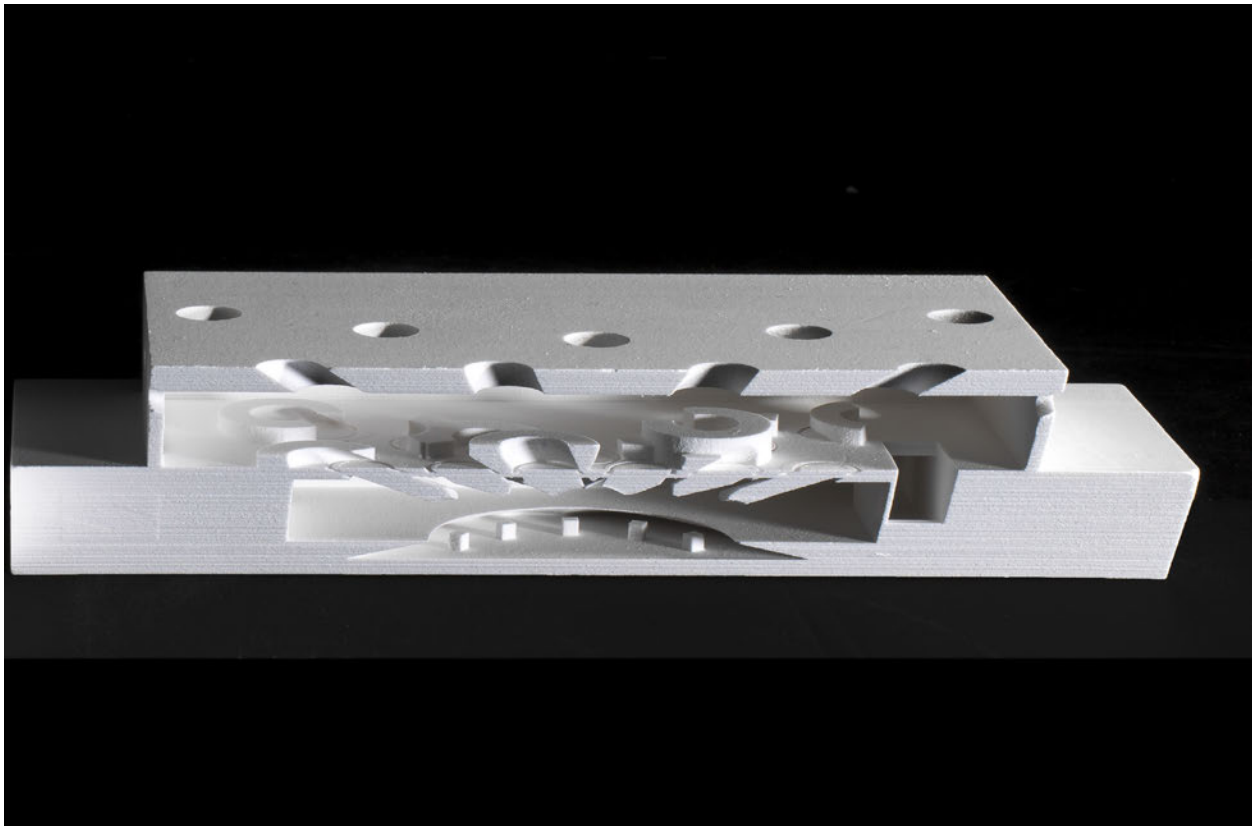
differ, the aim of collecting, distributing, and displaying sunlight is a central theme in both 42° and in Kahn's work.

The drawn representation continues the relationship by imitating Kahn's typical drawing style (above and on page 24). The drawings are rendered with black poché, clean line-weights, and patterning which describes surface materials.

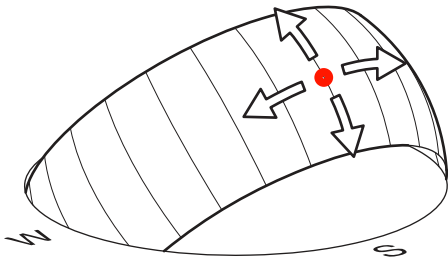
42°



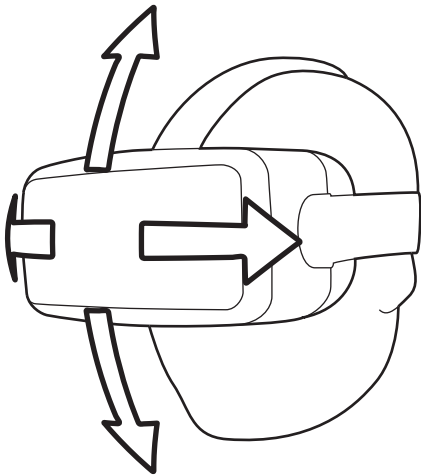
43 | 3d print section looking east



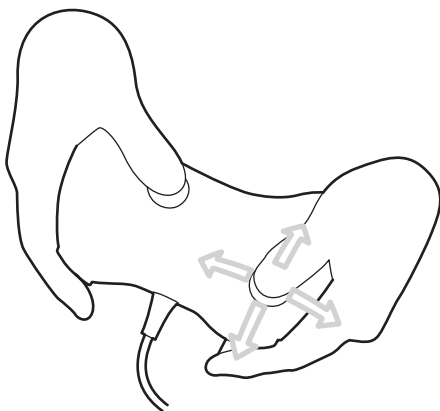
44 | 3d print section looking west



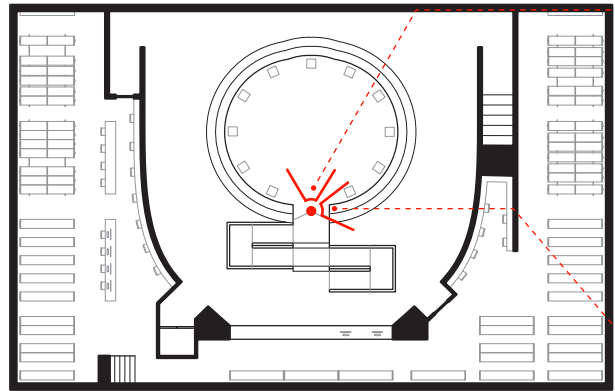
Can control time of day and day of year



Can control view direction



No movement

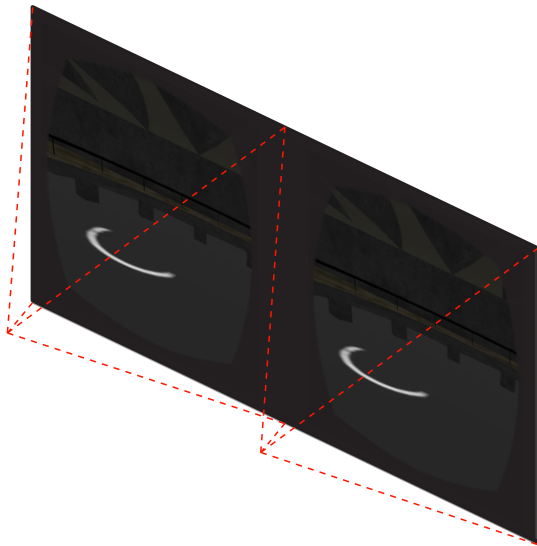


42° is well suited to the medium of virtual reality because the filtered sunlight can be fully experienced from one location in the building. The viewer is placed at standing height at the bottom of the set of stairs which lead down into the reading well. From here the entire floor of the well is visible and by turning their head the viewer can also see the surrounding public area of the basement level.

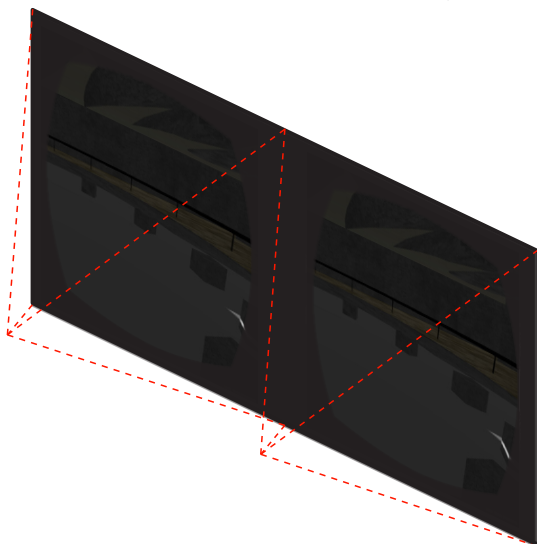
The playback speed is set to real-time so that the user is confronted with an apparently static arc of light in front of them. By using a joystick the user can change the time of day and the time of year to explore the relationship between time and the projected light geometry. Pressing a button also allows time to be sped up so that the movement of the arcs of light across the floor becomes visible.

Because the light is calculated dynamically by the computer, the rendering of the space cannot be static as it is at 4°. The space is rendered dynamically by the computer and thus the quality of the rendering is noticeably inferior. However the use of pre-computed light maps and high quality textures can help to close this gap. One benefit to dynamic rendering is the potential to take advantage of head tracking for slight movement of the point of view. Though slight, this adds greatly to the feeling of immersion, negating some of the drawbacks of the dynamic rendering quality.

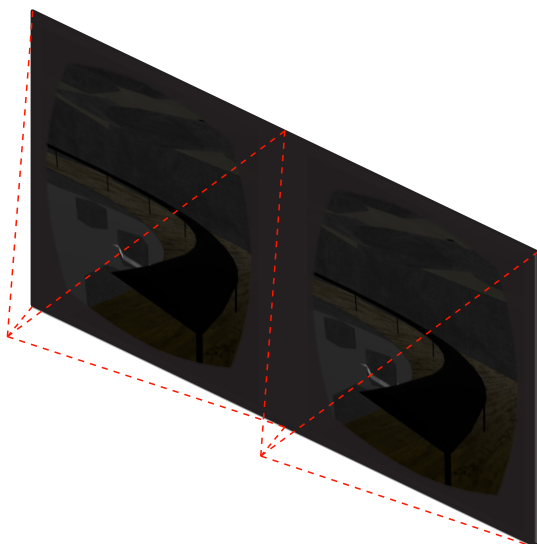
42°



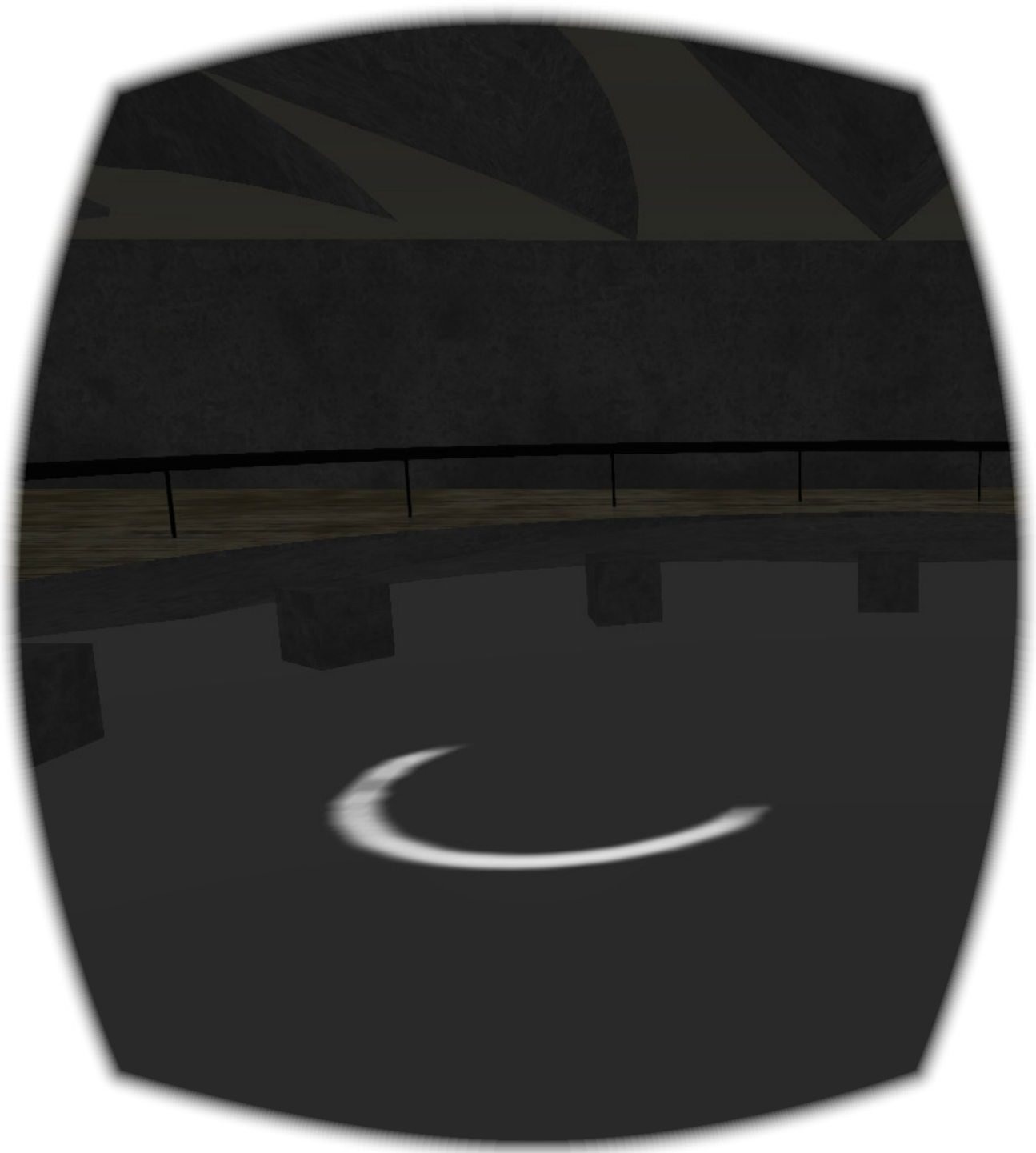
45 | 11:00s



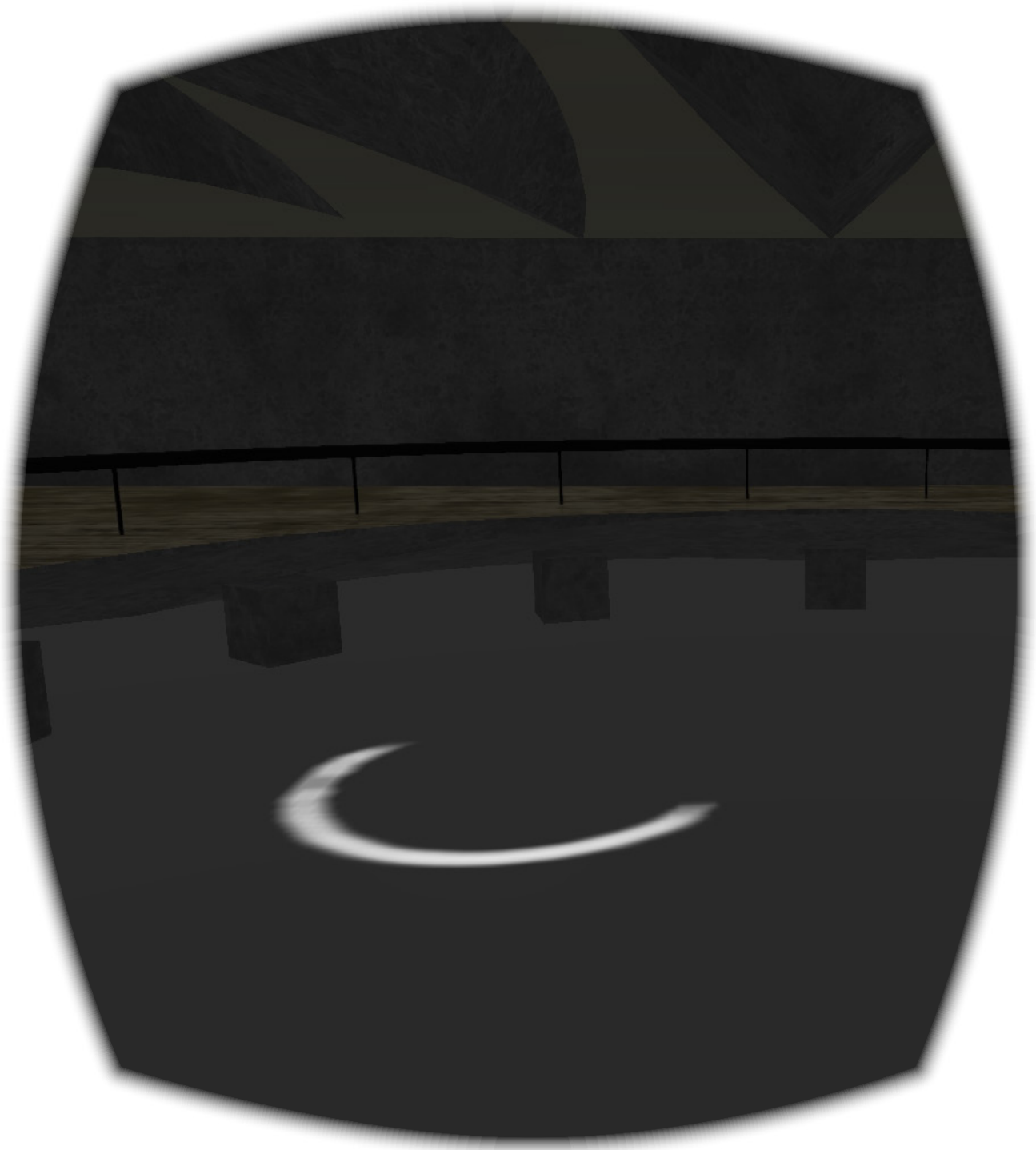
46 | 17:00s



47 | 17:00s

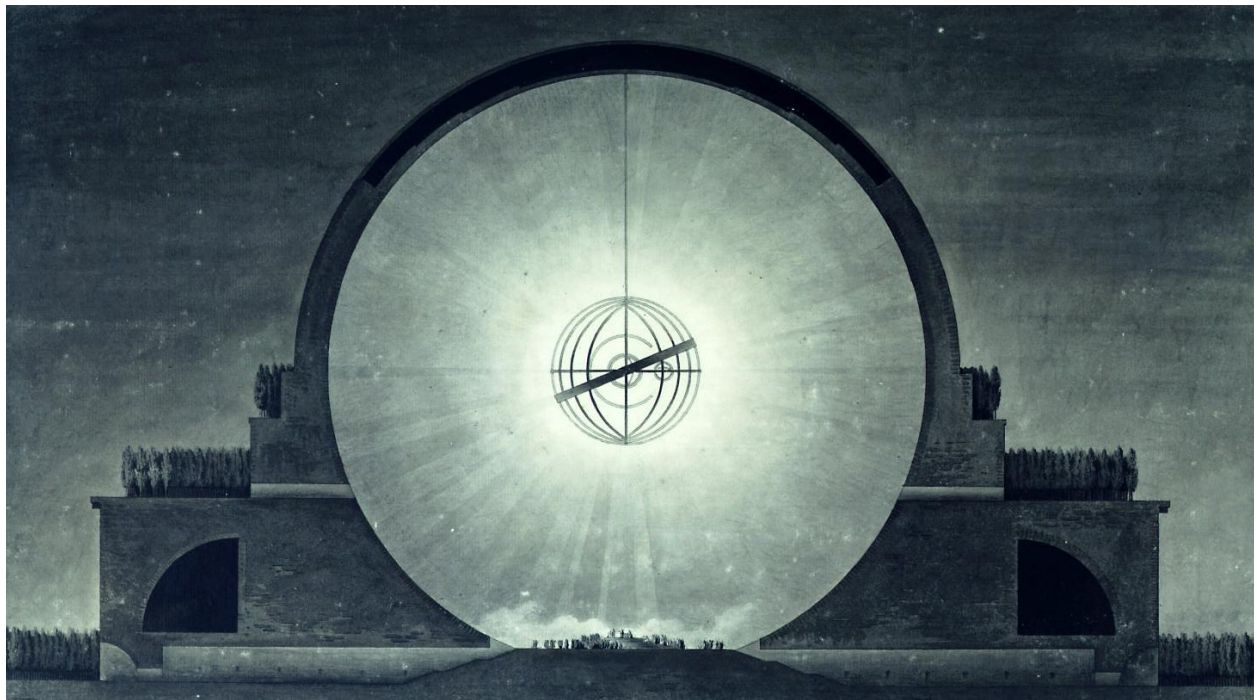


42°

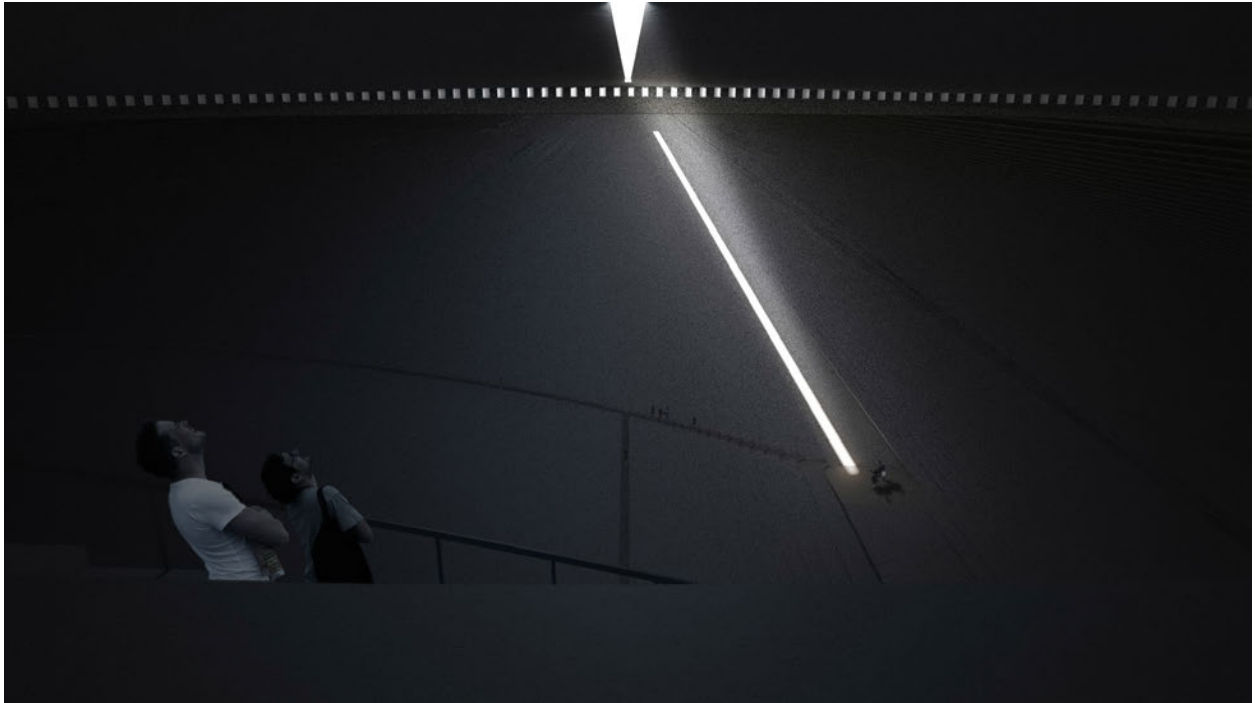




49 | **Section** (Photoshop: Tyler Swingle)



50 | **Cenotaph for Sir Isaac Newton** Étienne-Louis Boullée



51 | 6/22 7:35s (Photoshop: Luisel Zayas)

Étienne-Louis Boullée's Cenotaph for Sir Isaac Newton employs symbolic light and monumental scale to create an awe-inspiring experience. At night a brilliantly lit, giant armillary sphere illuminates the space (Fig. 50). The sphere's artificial, perfect illumination speaks to the Enlightenment ideals of reason and science.

78° is a variant of Boullée's cenotaph which employs a similar monumentality to tell a different story about light. Here sunlight becomes

visible as an entity inhabiting the space. The movement of the sun forms the building into a monument which exhibits solar rhythms.

The space takes the form of a hemisphere with a single linear skylight cut into the flat roof. The line of light cast by the skylight occupies a stair which encircles the space, allowing visitors to follow the light through its diurnal cycle.

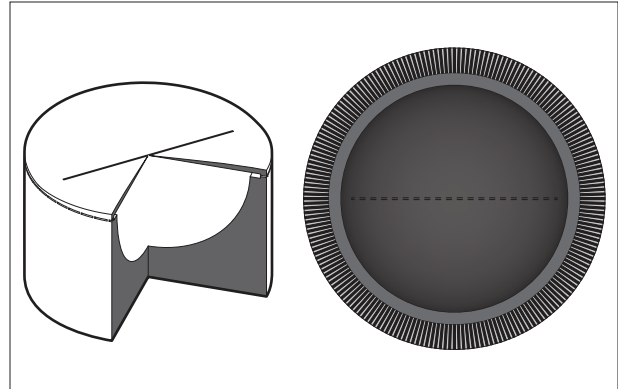
Method

The form of 78° centers around the occupation of the space by light and by people. The basic elements of a hemisphere and a linear skylight are shown in figure 52. Around the top edge of the hemisphere there is an occupiable gallery lined with windows. As the sun moves across the sky, the skylight traces out radial lines on the hemisphere. The location and length of these lines varies with the sun's position and thus is controlled by the building's location, the time of day, and the day of the year. Figure 53 shows the series of these lines that the sun traces out throughout the day on the summer solstice at 42° north latitude.

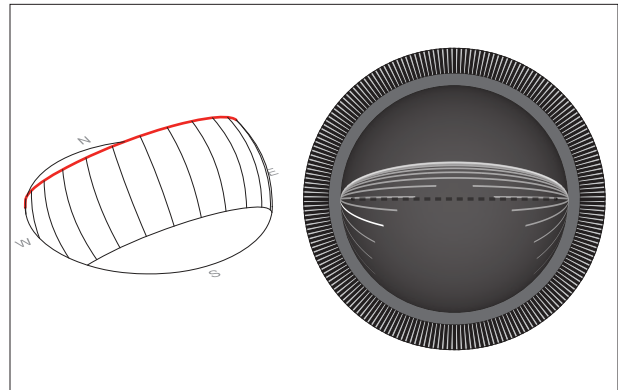
In order to align human occupation with solar occupation, a series of occupiable terraces cut into the hemisphere are aligned to these radial lines (Fig. 54). Thus the line of light created by the skylight always falls parallel to the edges of the terraces.

Because of the slope of the hemisphere these terraces are only occupiable at the bottom of the space. To connect the bottom of the hemisphere with the gallery at the top another form of circulation must be created which runs across the grain of the terraces.

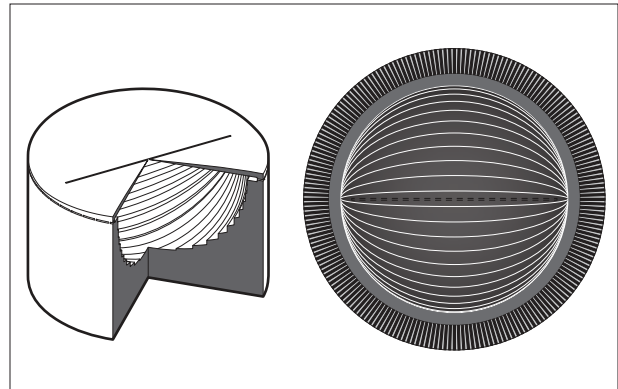
This second system is aligned to the path that the light from the skylight follows over the course of a day. On a given day of the year each end of the line cast by the skylight traces out a curve around the hemisphere (Fig. 55). On the summer solstice the sun is at its highest in the sky and thus this curve comes closest to reaching the bottom of the hemisphere. A stair



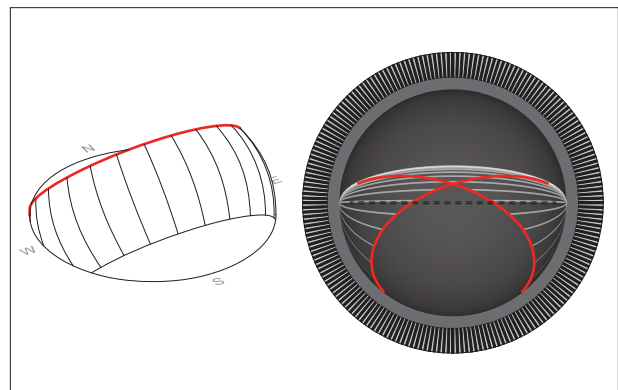
52 | Initial elements: Hemisphere and skylight



53 | Series of cast light 6/22, 42° north latitude



54 | Terraces aligned to sunlight



55 | Path of sunlight 6/22, 42° north latitude

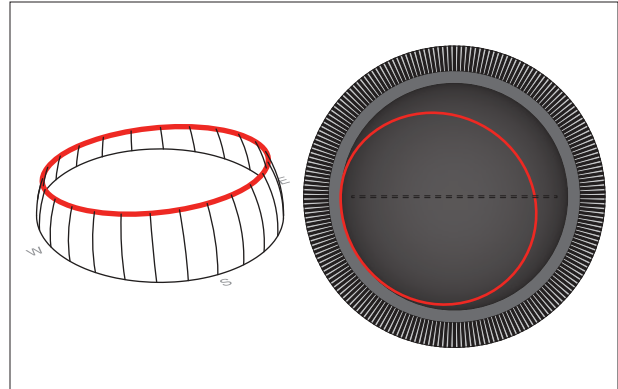
follows this curve, allowing for vertical movement through the space.

78° takes advantage of the particular path the skylight traces out at extreme latitudes. At lower latitudes the curve on the summer solstice dives too steeply down into the hemisphere to accommodate a stair (Fig. 55). At very extreme latitudes though, the slope of the curve at the very top becomes more gradual. 78 degrees north or south latitude marks the point at which the slope at the peak of the curve becomes amenable to a stair (Fig. 56).

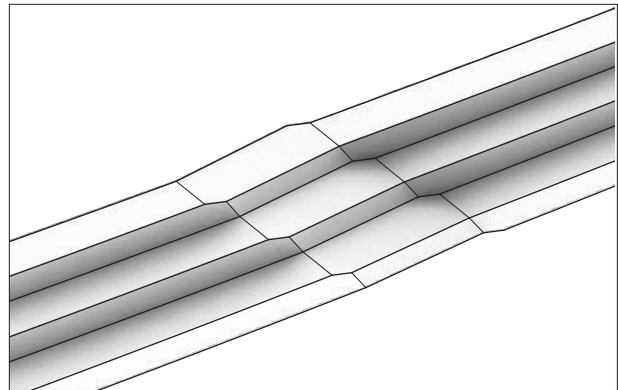
The stair following the solstice curve also generates the spacing for the radial terraces. The sides of each step turn into terraces which then follow the radial lines of the sunlight (Fig. 57). As the curve descends the hemisphere, the curve's slope combined with the orientation of the curve along the hemisphere cause the stairs to generate larger and larger terraces. At the very bottom of the curve one singularly large stair is created which also creates a large terrace that becomes the main occupiable space in the bowl of the hemisphere (Fig. 58).

The hemisphere is entered through a stair which connects the bottom of the space with ground level (Fig. 49 and 59). This stair continues up the side of the hemisphere to connect with the circular main stair. At its peak the main stair connects with the gallery around the top of the hemisphere.

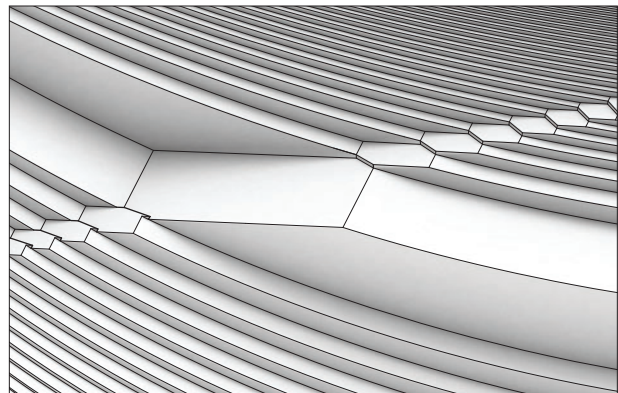
There is very little ambient light in the hemisphere in order to highlight the presence of the sunlight let in by the skylight. However, there is a glow of ambient light shed by the spaces in between the columns which hold up the roof. At the bottom of the hemisphere this glow manifests itself as a line of indirect light around the top of the space, contrasting with the line of direct light cast by the skylight.



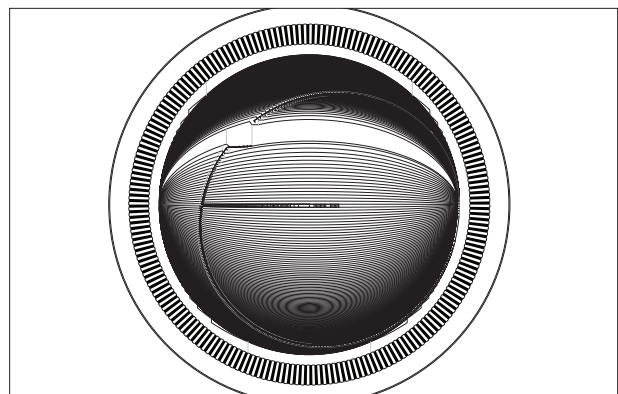
56 | **Path of sunlight 6/22, 78° north latitude**



57 | **Relationship between stair and terrace**



58 | **Large stair step at the bottom of the curve**



59 | **Plan**



78°



61 | **6/22 10:48s** (frame from animation)



62 | **6/22 14:24s** (frame from animation)



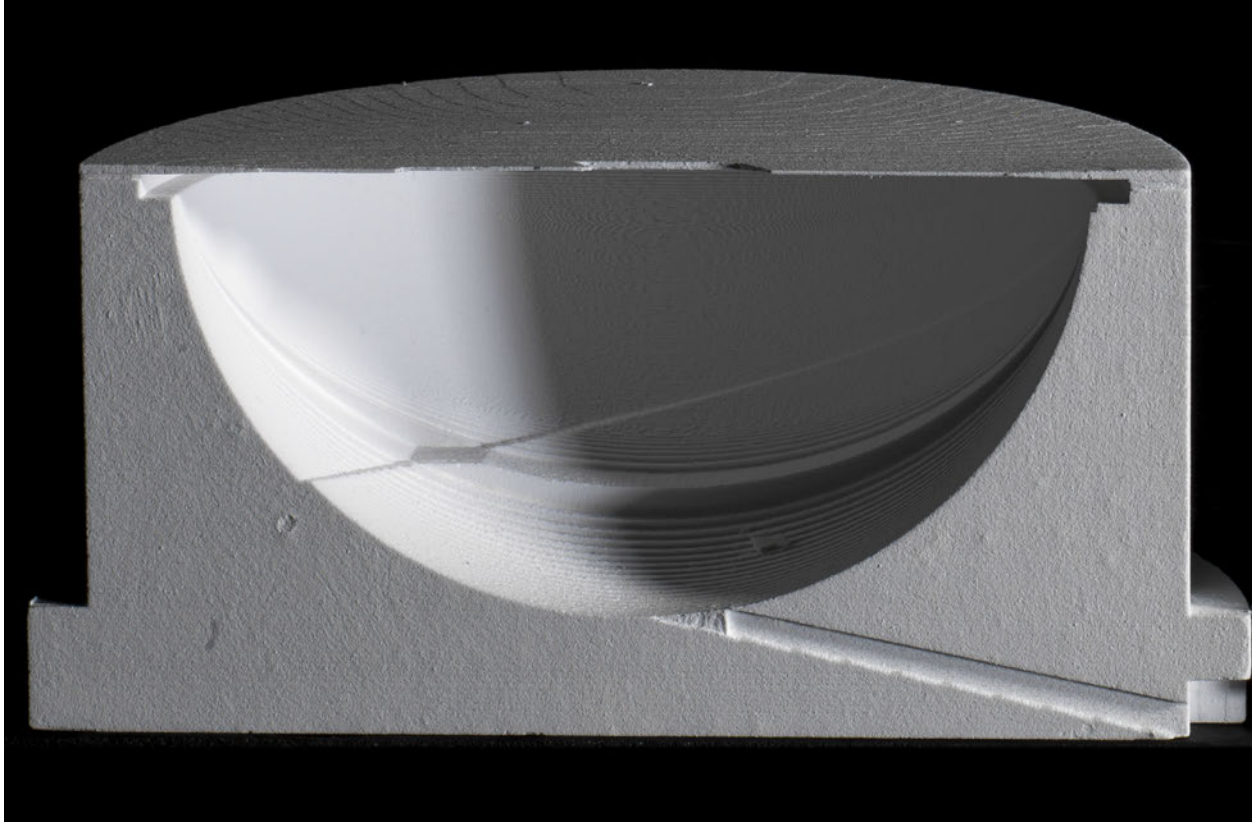
63 | **6/22 22:48s** (frame from animation)



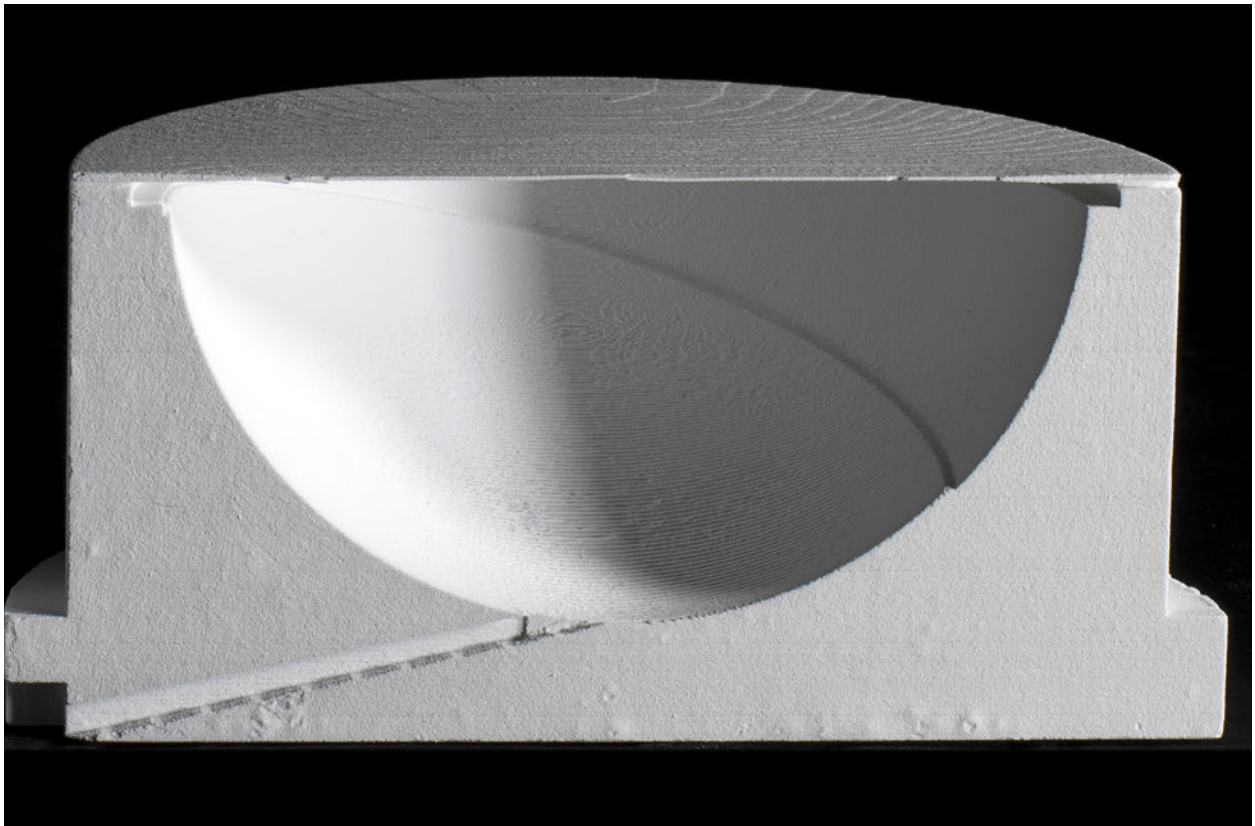
64 | **Plan** (Rendering: Tyler Swingle)

In keeping with the design heritage of Boullée, the drawn representation of 78° is also rendered in his style (above and on page 36). The drawings, especially the section, employ atmospheric lighting to convey the grandeur of the space. Both drawings depict the space under an overcast sky, representing the base lighting condition inhabited by the sunlight.

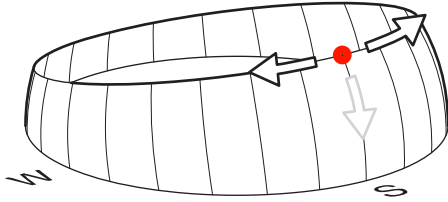
78°



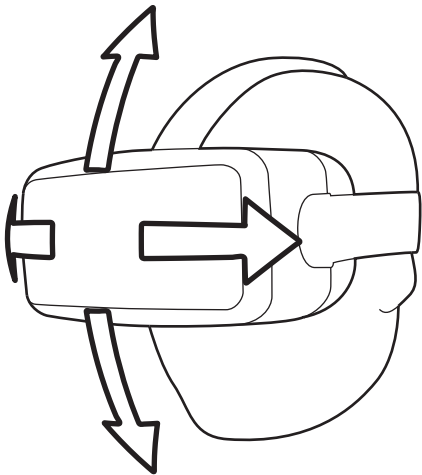
65 | **3d print section** looking north



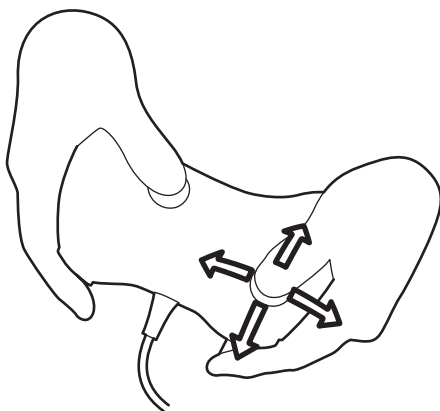
66 | **3d print section** looking south



Can control time of day, fixed day of year

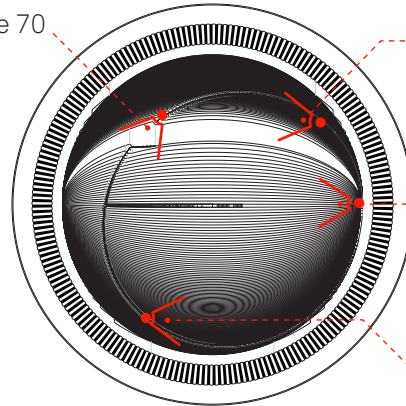


Can control view direction



Can move

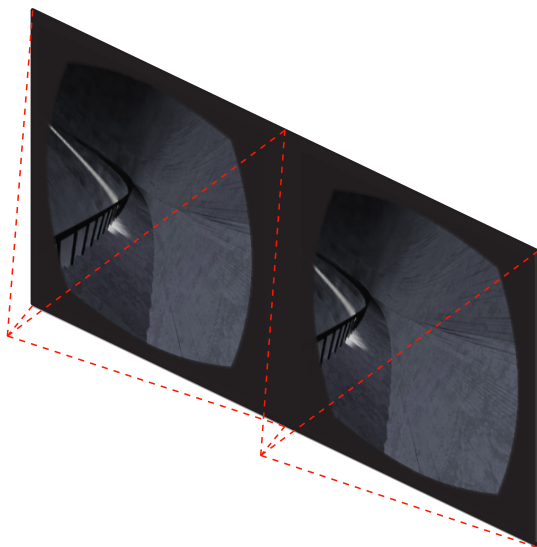
Figure 70



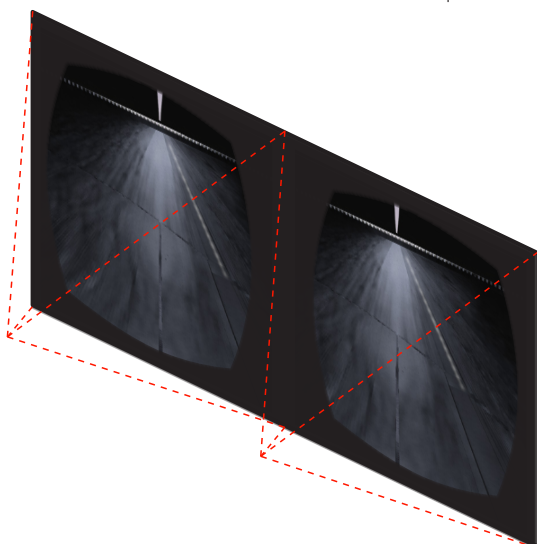
At 78° the sun and the people follow the same circular stair around the space. In order to experience the solar alignment, the viewer must be able to walk along the circular stair and view the space from all angles at all times of day. This requirement makes the virtual reality experience for 78° the most interactive of the three. The viewer is able to walk along the stair using a joystick and can change the speed at which time flows with a button, so that they can follow the sun around the space. The button toggles the speed of time between real-time and a speed at which the light moves along the stair at a walking pace. The day of the year is set to the summer solstice, when the sunlight traces out the path of the stair.

As with the virtual reality experience for 42°, the lighting and thus the rendering must be dynamic in order to change the time of day. Diffuse light maps are baked into all of the surfaces to improve the lighting quality.

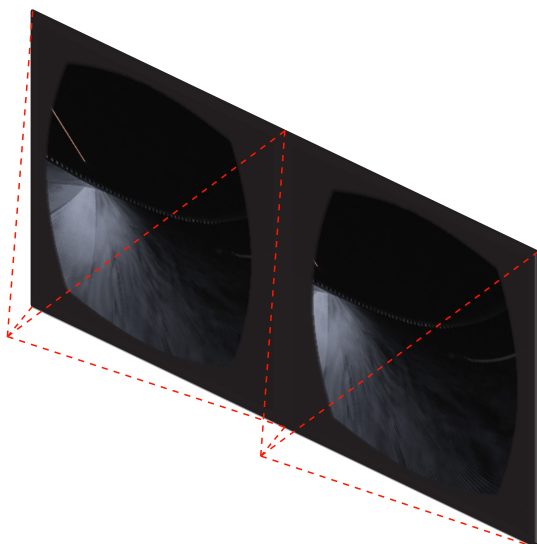
78°



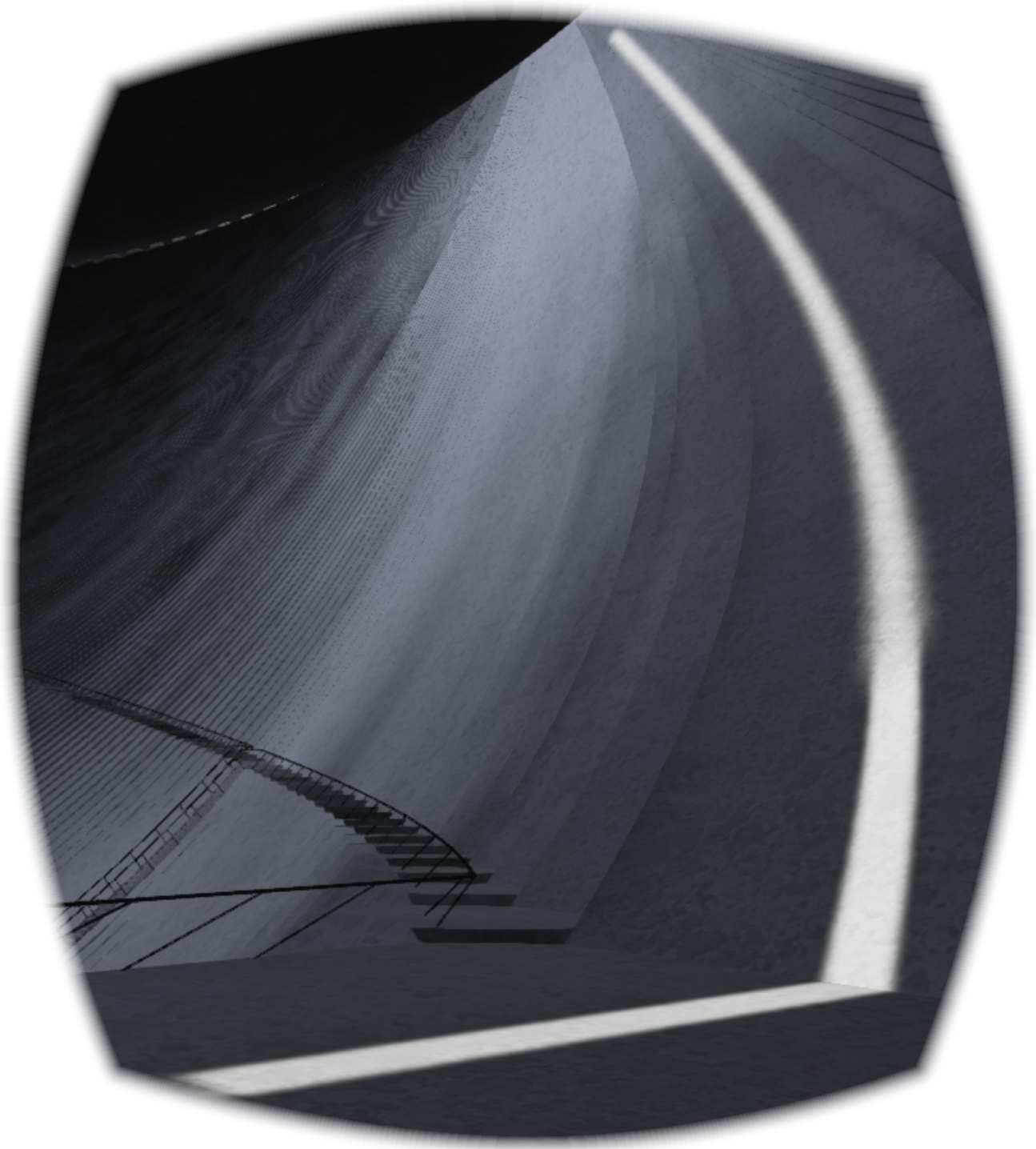
67 | 10:00s



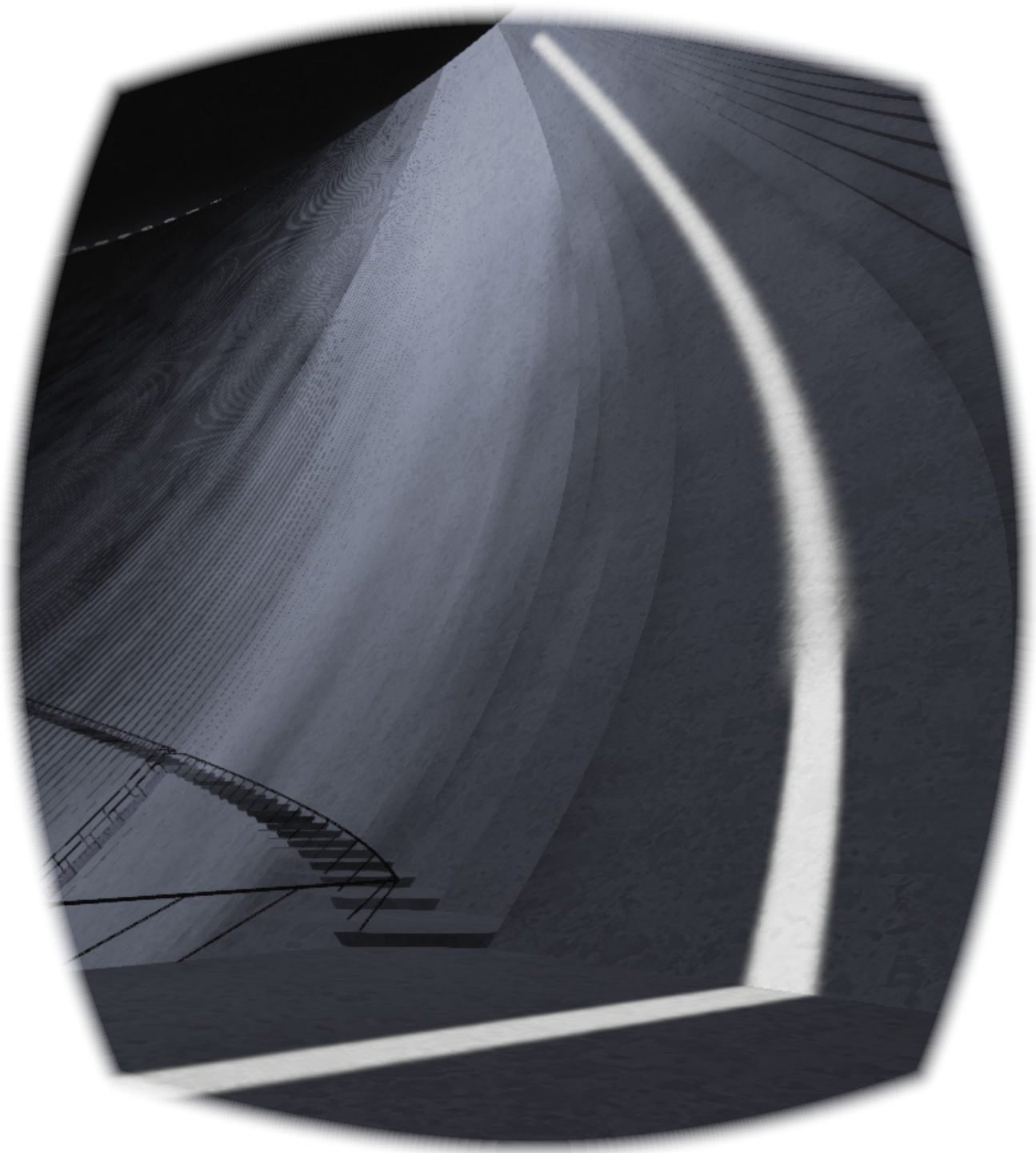
68 | 7:55s



69 | 1:36s



78°



70 | **6/21 7:55s** Virtual reality

Heliocentric Architecture

APPENDIX: TOOLS & METHODS



71 | **Astrolabe** Instrument used to predict the sun's position. Image: Francis Rolt-Wheeler

This thesis has always had two more or less distinct parts. The preceding buildings and their attendant representations made up the entirety of the final presentation of the thesis. However, they were each generated as a crystallization of a research into relevant tools and methods which occupied a significant part of the semester. The buildings are the physical objects by which these tools can be tested, verifying the claim that the tools can create awe-inspiring heliocentric architecture. However each building represents a narrow path taken through the field of possibilities opened up by the tools. If other paths are to be

explored, a detailed knowledge of the buildings themselves is not sufficient.

The next few pages endeavor to give an introduction into some of the more notable tools and methods that I have discovered and developed for this thesis. To simplify this discussion, particular software packages will be used by name however the methods are generalizable to other environments. A set of scripts, templates, and other potentially useful files is also available at the online home of this project: trygvewastvedt.com/heliocentric.

Solar Positioning

Heliocentric architecture by definition relies on the ability to accurately calculate the position of the sun at a given location and time. This is by no means a new ability. The alignment of Stonehenge and Newgrange to the solstice is proof enough that prehistoric civilizations had developed the ability to calculate where the sun would be in the sky. Thus since at least 3,000 BC architecture has employed a knowledge of the sun's annual and diurnal movements to calibrate structures.

The new capability that this thesis takes advantage of is the introduction of these calculations into a three dimensional computational environment. In this environment the calculation of the sun's position can be used as a driver for any number of parameters to generate and analyze the building's form. While the derivation of any one result of this method would be computationally possible with pencil, paper, and calculator (or abacus), the fluidity of design allowed by the integration of computation into the design environment enables the genesis of previously unthinkable, or at least impractical conclusions.

Most sources for calculating solar position start with latitude, longitude, and local time. As mentioned on page 11, the construction of local time facilitates human communication, but time zones, leap years, and daylight savings time all add layers of abstraction which calculations of solar position must account for. Because this thesis measures time using local solar time, much of this computation is avoided. In addition, by using a three dimensional parametric environment such as the Grasshopper plugin for Rhino, much of the trigonometry can be hidden by direct manipulation in polar coordinates.

The calculation requires a slightly more detailed understanding of the geometry of the solar swath. As shown in figure 72, the solar swath is a section of a sphere centered around the line the sun follows in the sky on the equinoxes. This line is inclined relative to the vertical by an angle equal to the site's latitude. On the solar swath the sun's position can be described with two coordinates: hour angle and declination.

Using latitude, hour angle, and declination to calculate the sun's position works particularly well for this thesis as the variables correlate directly with the three primary variables the buildings relate to: location, time of day, and time of year respectively.

The hour angle measures the current time in hours or degrees relative to solar noon. In figure 72 the local solar time is 18:00 and so the hour angle is 6 hours, or 90° (360° / 24 hours * 6 hours = 90°). The declination measures the angle between the sun's current position and the position of the sun at the same time of day on the equinox. In figure 72 the declination is approximately 16°. Accurately calculating the sun's declination using the day of the year is slightly more complicated:

$$\text{Declination} = -\text{Asin} \left(\sin \left(-23.44 \cdot \frac{2\pi}{360} \right) \cdot \cos \left(\frac{2\pi (N+10)}{365.24} + 0.033 \sin \left(\frac{2\pi}{365.24} (N-2) \right) \right) \right)$$

where N is the day of the year (January 1st = 1). Wikipedia has a clear derivation of the formula, but in short the complexity comes from accounting for the eccentricity of the earth's orbit.¹ One number of note in this formula is the 23.44 in the first line. This represents the obliquity of the earth's ecliptic, or the axial tilt of the earth relative to the normal of its orbital plane. This value changes over time, but very

1 http://en.wikipedia.org/wiki/Position_of_the_Sun#Calculations

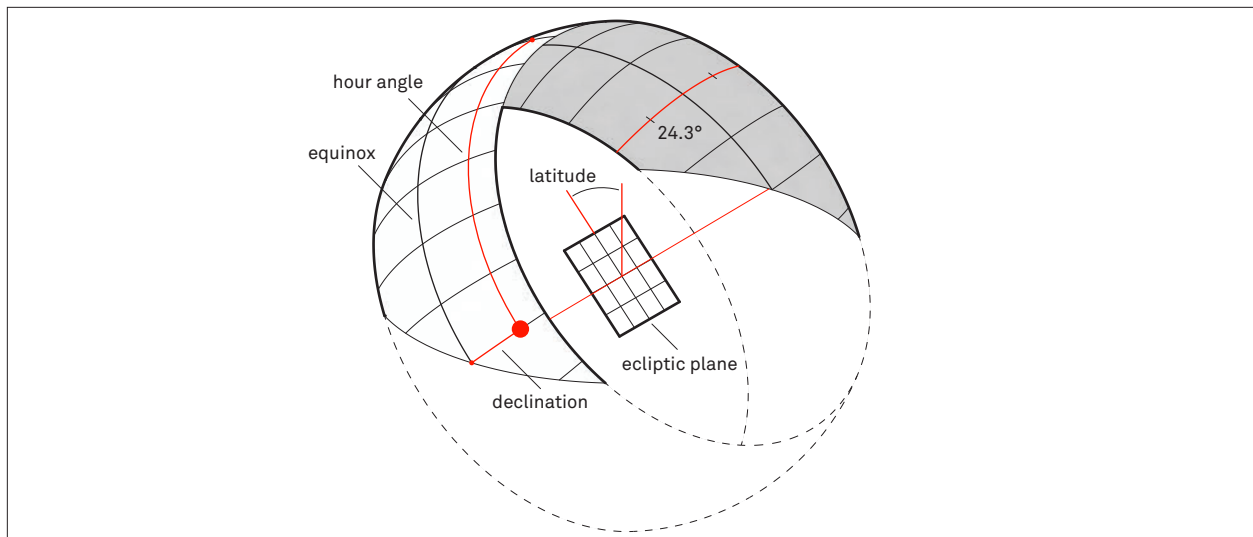
slowly. 23.44 will remain accurate until 2032, at which point the rounded obliquity of the ecliptic will be 23.43.²

As shown in figure 73, the calculation of the sun's position in Grasshopper proceeds much as in figure 72. The ecliptic plane is found using the obliquity of the ecliptic, the hour angle and declination are calculated using the formulas above, and the sun's position is found using polar coordinates in the ecliptic plane, where the horizontal angle is the hour angle

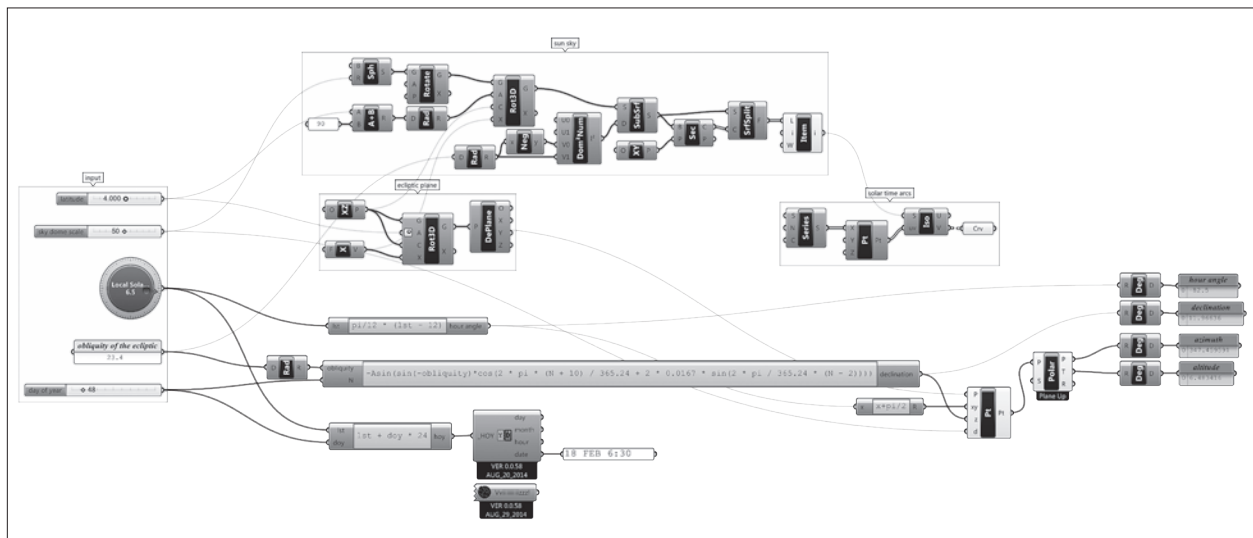
and the vertical angle is the declination. The plugin Ladybug is used only to convert the day of the year to a readable date for reference.

The power of this method is that the position of the sun is returned in Grasshopper as a vector which can immediately be used to generate building geometry. A list of values can also be entered for the day of the year or the time of day in order to generate a series of positions. Furthermore, the intermediate results of the ecliptic plane, solar swath, and hour arcs are also useful in creating geometry based on the sun's movements.

2 http://en.wikipedia.org/wiki/Axial_tilt#Short_term



72 | Solar swath and ecliptic plane

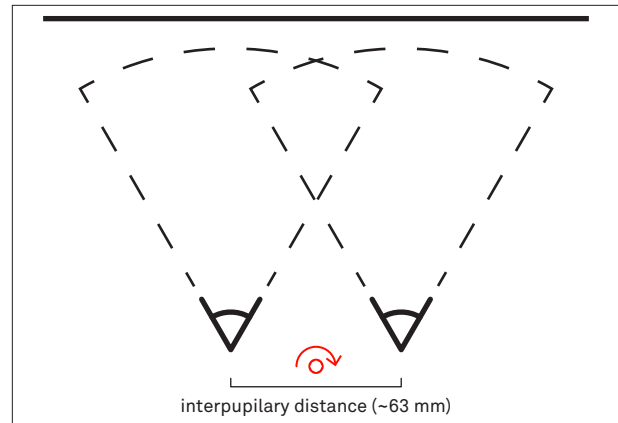


73 | Solar positioning in Grasshopper

Virtual Reality

The most obvious way of creating content for virtual reality, given its prominence in the gaming world, is to create some form of a three dimensional video game. Tools such as Unity and Unreal Engine already have built-in capability for rendering a game from each eye and displaying those renderings on the screen with the appropriate distortion and chromatic aberration. This makes sense when making use of the full interactivity of the game environment, such as with the virtual reality experiences at 42° and 78°. However when, as at 4°, the virtual reality experience requires neither dynamic movement in three dimensions nor control over the environment, it makes more sense to directly render one or more static scenes at a much higher quality than is possible with dynamic rendering.

The simplest way to render such an image would be to treat its display in virtual reality as a window (or a table) roughly stretching across the viewer's field of view. If the rendering exists as a window in virtual reality, then each eye sees the content inside the window from a different but static angle and two traditional renderings can be created from two different perspectives (Fig. 74). However this method does not take full advantage of the potential for virtual reality to create an immersive environment, placing the viewer into the picture itself. In order to do that the rendering must cover the surface of a sphere that encases the viewer (Fig. 75). Such a rendering is often termed a spherical panorama. The sphere can be unwrapped into a flat image in a number of different ways but the most common in this context uses an equirectangular projection which maintains an even spacing of latitude and longitude lines. Significant distortion

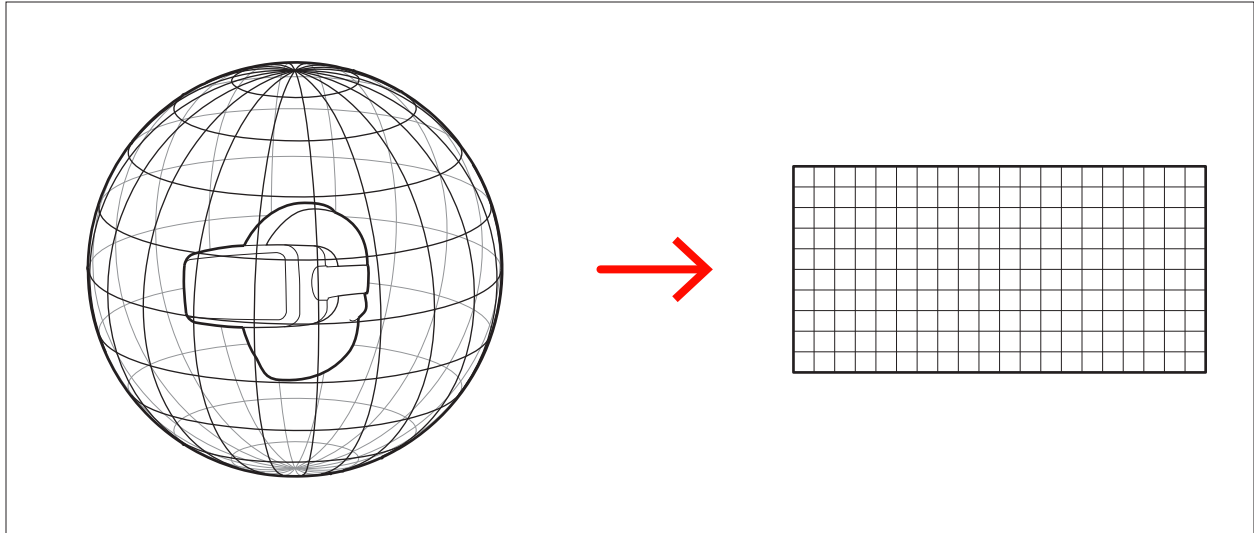


74 | **Stereoscopic view of traditional rendering**

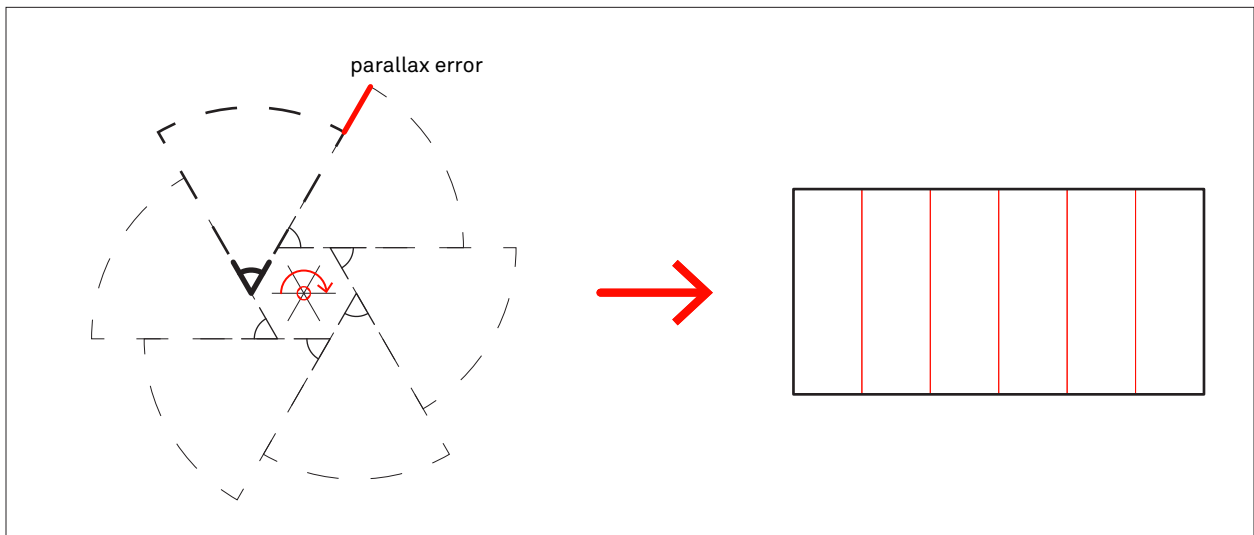
occurs at the poles, but these are rarely the points of visual focus.

The complications arise when an attempt is made to add stereoscopy to a spherical panorama. As the viewer rotates their head to look around a scene, the position (as well as the orientation) of each of their eyes changes. Thus the spherical panorama must be rendered in strips from a series of different positions (Fig. 76). However, since an object appearing in multiple strips will be rendered in pieces, each at a different distance from the camera, the seams between the strips will create visual discontinuities in the composite rendering. This visual error can only be eliminated by maximizing the number of strips, rendering each column of pixels in the spherical panorama from its own unique position (Fig. 77). In theory this only reduces the problem, but in practice the discontinuities become invisible in the rendered image.

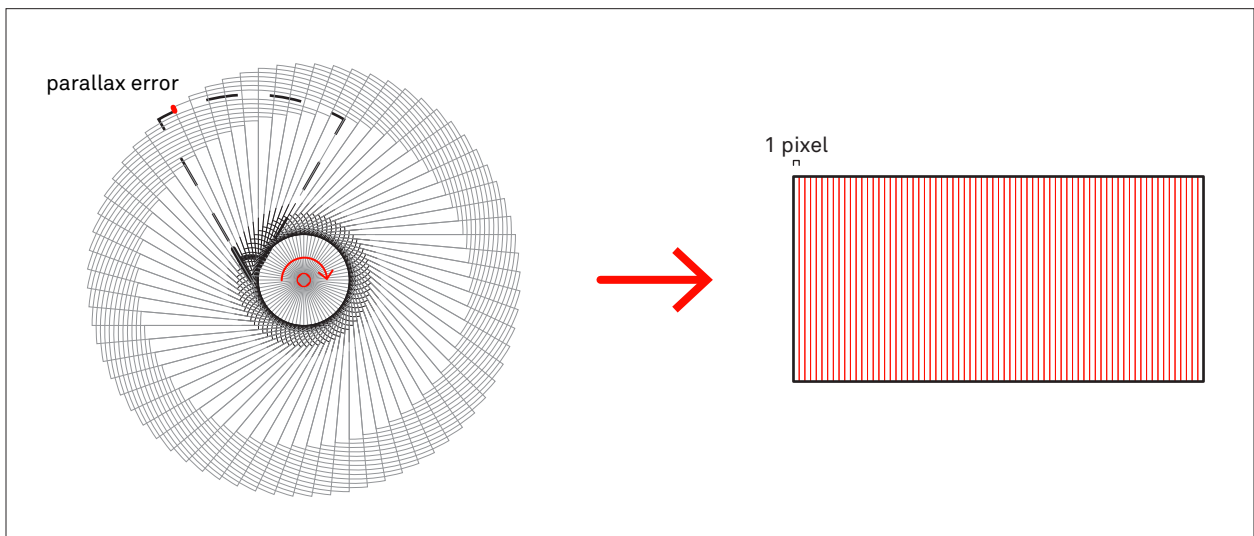
At the resolutions required for virtual reality this is impractical to do manually. Shaders have been written for several rendering applications which automate the process, creating accurate stereoscopic spherical panoramas directly by internally computing the appropriate camera position at each pixel.



75 | Spherical panorama using an equirectangular projection



76 | Parallax error from a coarse approximation of a stereoscopic panorama



77 | Elimination of visible parallax error

Tools

Mundane as it may be, some record of the particular tools I used in this thesis and the reasons for those choices might become useful. For most of the technical elements of the thesis I found myself on the bleeding edge, which is aptly named. Many solutions were not ideal, few were elegant, and nearly all will be outdated in five years. Nevertheless, perhaps this record can serve as a starting point for future investigations into these media. Examples of several of these solutions can be found in the resources at trygvewastvedt.com/heliocentric.

One tool that is unlikely to become passé in the near future is Grasshopper. Grasshopper formed the technical foundation for nearly everything I did, from creating building geometry to generating animated diagrams. With two exceptions the scripts used very few additional plugins and were built from the solar positioning script outlined on page 50. One exception is the analysis of indirect illumination shown in figure 16. This script makes use of the “Forward Raytracing” component in the Ladybug plugin to generate the rays of sunlight.

The other exception is the animated diagrams. These proved to be tricky to produce as I was unable to find a program specifically tailored to creating animated vector diagrams of three dimensional geometry. The solution I ended up with exists as a Grasshopper definition with a slider which can be animated to record a series of screenshots of the Rhino viewport. Key components include Ladybug’s “Orient to Camera” to draw geometry normal to the view direction, Human’s “Preview Lineweights” to draw lines of varying thicknesses, and the built in “Create Material” component with a black

diffuse and specular color to create masks which allowed for hidden line wireframes.

The rendered plan animations are composites of a diffuse rendering in Maxwell (sun turned off), static vector linework, and a V-Ray animation rendered from 3ds Max. At this time it is not possible for a V-Ray camera in 3ds Max to have an orthographic lens, but using the default camera type works just fine. The position of the camera in space controls the position of the clipping plane (though a non-zero near clip could also be used) and the camera’s field of view controls the zoom level without affecting the projection. I composited the V-Ray Raw Total Lighting render element using the “Linear Dodge (Add)” blend mode in Adobe Premiere Pro.

Rendering the light for the animated diagrams was more complicated, particularly for 4° which involved dynamic geometry. This animation was done using the Centipede plugin for Grasshopper, which facilitates keyframed animation. Though I used the full setup as demonstrated in the Centipede example file, only the “renderAnimation” component is strictly necessary if no complex keyframing is being done. The component triggers a rendering in Rhino at each step of the animation. If the V-Ray global option “Batch render” is turned on, V-Ray pauses the Grasshopper script while each frame is rendering.

Some of the technical details behind the virtual reality solutions have already been discussed (page 52). The static stereoscopic spherical panorama used for 4° was rendered in V-Ray from 3ds Max. This is one workflow which is likely to get significantly easier in the near future. At the time of this thesis there was no public plugin for 3ds Max which allowed such an image to be rendered directly. However, Andrew Hazelden and Roberto Ziche are currently developing one which will likely be ready soon (<https://github.com/zicher3d-org/domemaster-stereo-shader>). For me the workflow involved exporting a V-Ray scene file from 3ds Max, editing the scene definition to

use the stereoscopic camera, and then rendering in V-Ray Standalone.

The display of the panorama in the Oculus Rift was done using Whirligig, a media viewer built for the Rift. The two renderings (one from each eye) were combined in Photoshop into a square over/under stereoscopic image which is a format that Whirligig can display.

For the more interactive virtual reality experiences I used Unreal Engine 4. I started building a virtual reality environment from scratch but ended up using a template found here: <https://github.com/mitchemmc/UE4FirstPersonVRTemplate>. This is probably the way to go, but there is a lot going on in the template and so in some ways the workflow from scratch was simpler as I knew precisely which scripts were affecting what. Hopefully much of this will slowly become standard in Unreal Engine itself, which would greatly simplify this process.