HALO
Re-forming Architectural Space with Light Caustics
by ZHAO MA

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Submitted to the Department of Architecture in partial fulfillment of the requirements for the degree of Master of Architecture at the MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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HALO
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ABSTRACT

What form can light take?

Light has been an eternal theme in architectural design. Light defines, shapes, and transforms space in various ways. However, the way light has been used in human history has not changed: the variation of space is a result of the interaction between light and shadow along with the geometry and materials that defines the space itself.

Through the BLOCKING of light comes the variation of shadows.

Is it possible to extend the possibility of light from a basic level?

This thesis questions one of the fundamental uses of light in architectural space: how can we use light beyond the realm of shuttering? With the implementation of a set of state-of-the-art algorithms in computer graphics field, the thesis presents a serious of explorations in how refraction can re-form the architectural experience using the movement of light in both still and dynamic ways.

Through the REDISTRIBUTION of light comes the variation of time.

Thesis Advisor: Brandon Clifford
Title: Assistant Professor of Architecture
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Background

How nature uses light?

As a typical type of atmospheric optics created by the natural light, halos bestow a delicate beauty to the skies and tell us about the crystals inhabiting the clouds.

Ice halo displays range from the familiar circle around the sun or moon to rare and prized events when the whole sky is webbed by intricate arcs.

Tiny ice crystals in the atmosphere create halos by refracting and reflecting light.
Halo & Caustic
How nature uses light?

As a typical type of atmospheric optics created by the natural light, halos bestow a delicate beauty to the skies and tell us about the crystals inhabiting the clouds.
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Tiny ice crystals in the atmosphere create halos by refracting and reflecting light.
Scientists have categorised different types of halos with different visual effects.

These halos have similar caustics explanation but each slightly differs from the others.

refraction:

*The fact or phenomenon of light, radio waves, etc. being deflected in passing obliquely through the interface between one medium and another or through a medium of varying density.*
Similar effects also exist in daily life, through water surface, glass surface, etc.

The essence behind all these natural or artificial effects are the refraction of light, or to be more specific, caustic effects.
caustic:

*Formed by the intersection of reflected or refracted parallel rays from a curved surface.*
Background

How architecture uses light?

There are tremendous examples to show how we human beings utilise the light to interact with space and create sensational experience within.

But are we done with it?

By examining the existing implementation of light fixtures, installations, artefacts, as well as buildings integrated with light, it is amazed to find we didn’t know much about light when it is no longer transmitted only in air.
Light in Architecture
"The Church of the Light embraces Ando's philosophical framework between nature and architecture through the way in which light can define and create new spatial perceptions equally, if not more so, as that of his concrete structures."
"Within Intersections, no clear boundary or separation exists; our moving bodies change the nature of the pattern as we walk freely through its dense silhouette."
Tunnel Installation - James Turrel

"The precise frame lines set in contrast to diffuse light in order to let the viewer experience transcendental passages playing with the boundaries and elements of the sky."

Light diminish the sense of space.
The Louvre Abu Dhabi Museum - Ateliers Jean Nouvel

"It is rather unusual to find a built archipelago in the sea;

it is even more uncommon to see that it is protected by a parasol flooded with a rain of lights."
Statement
Architecture should interact with light and shadow beyond the traditional realm to create new type of space. A deeper understanding and control of the light should derive an intuitive design process of architecture with light – the delight of light.
Light Exploration

From the fundamental properties of light and a series of experiments and tests, this chapter explores the basic interaction of lights and refracting surfaces.

Intuition here is very important to help learn how light performs and how we can abstract the physical properties into mathematical form for further development.
The Fundamental Property of Light
Light beam in Reflection & Refraction
Reflection & Total Reflection
Light Exploration

Modern rendering software can already simulate the physical transmission of light in a very accurate level.

To get an intuitive sense about how transparent surface with different curvature will re-direct light, we use Maxwell Render 3.0 to simulate the effect of light refraction in order to guide us for the design of light in later part.
distance = 1  distance = 4  distance = 7

the divergence of light through a concave surface
Light Rendering Test
distance = 1  distance = 4  distance = 7

the convergence of light through a convex surface
distance = 3  

distance = 5  

distance = 7  

the divergence of light crossing
the gradient change through a gradient inclined surface
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light refraction of different distance through simple surface
HALO | RE-FORMING ARCHITECTURAL SPACE WITH LIGHT CAUSTICS
light refraction of different distance through simple surface
photo of physical test
photo of physical test
photo of physical test
photo of physical test
Light Exploration
Through the series of rendering simulation, it can be discovered that unlike the method widely used in lighting design/designing light -- through "BLOCKING", the refraction never shutters any light -- it is through the method of "REDISTRIBUTING" that light rays are redirected to different positions. The amount of light shed in the same amount of areas is never changed.

Through the redistribution come light and shadows.
Computation
Design Direction

To control the shape of a caustic design, two central computations need to be addressed:

1. How to simulate, i.e. compute, the caustic generated by a given surface.
2. How to change the surface geometry such that it focuses and diverts incoming light to produce a desired caustic image.
HALO RE-FORMING ARCHITECTURAL SPACE WITH LIGHT CAUSTICS
Forward: Refraction Surface -> Caustic Patterns
Design direction: bottom-up

Backward: Caustic Patterns -> Refraction Surface
Design direction: top-down
Computation
Computing Caustics

As shown on the next page, for computing caustics, we use a computation model similar to ray tracing but only compute the refraction of the light rays based on the refractive surface.
incoming light

refracted light

compute surface normals

integrate normals to heightfield
A simple mesh surface is chosen to compare the computation result with the rendering simulation. The density of the points represents the intensity of the light illumination.
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Computation
Designing Caustics

The backward computation – designing a surface that can refract light into specific patterns is achieved by implementing a series of academic papers in computation graphics field. A simple explanation is shown here. More details can be found in the Bibliography part at the end.
SCHWARTZBURG, Y. et al., High-Contrast Computational Caustic Design, ACM Transaction on Graphics (TOG) 33, 4, 74

algorithm overview
Optimal Transport Map Computation  

Natural Neighbor Interpolation  

Target Optimization  

SCHWARTZBURG, Y. et al., High-Contrast Computational Caustic Design, ACM Transaction on Graphics (TOG) 33, 4, 74

three main steps in the algorithm
The Delight of Light
In this section, we use the implemented algorithm directly to see how precise we can control the refraction of light. Three images are chosen as targets to compute the corresponding surfaces that can refract light to, with different sampling density.

Rendering images are compared with the original target images and two of the computed surfaces are manufactured physically to prove the results.
target image

sampling density: 250 x 250
rendering result from mesh surface

mesh density: 200 x 200
target image (testing precision on boundary)

sampling density: 300 x 300
rendering result from mesh surface

mesh density: 300 x 300
target image (testing precision on boundary & gradient)

sampling density: 350 x 350
rendering result from mesh surface

mesh density: 350 x 350
physical lighting test

light source: distance spot light (to simulate parallel light)
physical lighting test

light source: distance spot light (to simulate parallel light)
The Delight of Light
This project discusses the “ambiguous” possibility of “light redistribution” through time and space.

A specified space and a refractive surface are created from two reciprocal ambiguous heightmaps. The roof will distribute sunlight to create different ambiguous spatial effects during different times of the day. Transitional velocity also varies because of the change of the angle between sunlight and the horizontal surface.
roof

heightmap
ground

heightmap
roof

3D mesh model
ground

3D mesh model
ground

contour
top rendering of the refracted light

sunlight direction perpendicular to the ground
a typical view angle of light dynamics

sunlight direction perpendicular to the ground at noon
photo of the test model
photo test model
continous framing of light distribution throughout a day

sunlight direction perpendicular to the ground at noon
continuous framing of light distribution throughout a day

sunlight direction perpendicular to the ground at noon
The Delight of Light
The "Dynamic: flow" aims to zoom at the dynamic property of light flow through the continuous movement in a specifically designed circular space.

The light folds, separates, crosses, and distributes along the space to create different sensational experience when walking around the space.
roof

3D mesh model
ground

3D mesh model
roof
contour
ground

contour
top rendering of the refracted light

sunlight direction perpendicular to the ground
a typical view angle of light dynamics

sunlight direction perpendicular to the ground at noon
photo of the test model
contineous movement in the circular space

sunlight direction perpendicular to the ground at noon
The Delight of Light
Dynamic: rise

In this project, the space is designed by following the Fibonacci curve to create a constant increasing speed and projection distance. (137.5°)

Various pieces of refraction surface are used to explore the multiple possibilities of light patterns projected on deformed receivers.

These projections reveal the dynamic and artistic aspect of light where precision here has the least importance.
contours of the inner space
photo of the looking device
refractive surface and its corresponding contours
rendering simulation
refractive surface and its corresponding contours
rendering simulation
refractive surface
rendering simulation
By further developing the possibilities of refractive patterns, we could use multiple refractive pieces overlayed by each other to make even more complex refraction composition.

Some of the selected results is shown here, presenting the artistic and complexity potential for the system.
rendering simulation
Bibliography