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Recreating Early Islamic Glass Lamp Lighting

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Abstract

Early Islamic light sources are not simple, static, uniform points, and the fixtures themselves are often combinations of glass, water, fuel and flame. Various physically based renderers such as Radiance are widely used for modeling ancient architectural scenes; however they rarely capture the true ambiance of the environment due to subtle lighting effects. Specifically, these renderers often fail to correctly model complex caustics produced by glass fixtures, water level, and fuel sources. While the original fixtures of the 8th through 10th century Mosque of Córdoba in Spain have not survived, we have applied information gathered from earlier and contemporary sites and artifacts, including those from Byzantium, to assume that it was illuminated by either single jar lamps or supported by polycandela that cast unique downward caustic lighting patterns which helped individuals to navigate and to read. To re-synthesize such lighting, we gathered experimental archaeological data and investigated and validated how various water levels and glass fixture shapes, likely used during early Islamic times, changed the overall light patterns and downward caustics. In this paper, we propose a technique called Caustic Cones, *a novel data-driven method to 'shape' the light emanating from the lamps to better recreate the downward lighting without resorting to computationally expensive photon mapping renderers. Additionally, we demonstrate on a rendering of the Mosque of Cordoba how our approach greatly benefits archaeologists and architectural historians by providing a more authentic visual simulation of early Islamic glass lamp lighting.*

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Picture/Image Generation—Display algorithms

1. Introduction

Interior lighting in early Islamic and Byzantine environments comprised single jar lamps or polycandela [Gol92]. Through the combination of glass, water, fuel and flame, these appear to have been designed to cast down unique caustic lighting patterns, to enable navigation and even reading for study groups. In this paper we investigate the lighting in the Mosque of Córdoba from the 8th through 10th century. Although none of the original fixtures from the site have survived, through collaboration with historian experts, we have drawn on fittings and lamps from earlier and contemporary sites and artifacts. Our goal is to use a set of valid experimental data in order to accurately model complex caustic light source effects and thus reconstruct authentic illumination within the 10th century Mosque of Córdoba in Spain [Cre40]. The Mosque of Córdoba underwent a significant expansion, enhancement and decoration by al-Hakam II in 940CE [Ewe68].

Various physically based renderers, such as RADIANCE [LS98], and photon mappers are widely used for realistic lighting models of ancient architectural scenes, for example [CRL06, DC01]. Although more accurate than contemporary renderers which only compute ambient light, even these physically based renderers are rarely able to capture the true ambiance of the environment due to subtle lighting effects. Specifically, these renderers often fail to correctly model complex caustics produced by glass fixtures, water level, and fuel sources. Simulating such accurate results is important, as the caustic patterns can create functional space-specific illumination (such as for reading) or a specific mood and atmosphere within a mosque that are of great archaeological interest when analyzing any reconstruction and visualization of the site.

In this paper, we describe a series of experimental studies which investigated and validated how various glass fixture shapes and water levels were likely to have been used. Such details can significantly alter the fixture's overall light patterns and downward caustics. Based on the results of these studies, we propose a technique called *Caustic Cones*, a novel data-driven method to 'shape' the light emanating from the lamps. Such an approach accurately recreates the complex downward lighting without resorting to computationally expensive photon mapping renderers. Through *Caustic Cones* we are able to provide high-fidelity visual simulations of medieval Islamic glass lamp lighting and thereby allow art and cultural historians new insights into how the interiors of mosques may have been perceived in the past.

2. Prior Work

Most common computer graphics rendering techniques do not readily yield caustics. Ray tracing [Whi80] casts rays from the eye into the scene, and therefore cannot directly produce caustics. Modeling caustics involves utilizing a global illumination approach to create the indirect light [DBB03]. Arvo [Arv86] proposed Backward Ray Tracing for modeling caustics which involved tracing rays from the light source, as opposed to the eye, introducing a preprocessing step for caustics. Kajiya [Kaj86] described how light is propagated through a Monte Carlo method called *Path Tracing*. Bidirectional path tracing, proposed by Veach and Guibas [VG95], traced paths from both the eye and the light source. Dutré et al. [DLW93] used an efficient Monte Carlo approach for modeling caustics. All these methods are computationally expensive due to explicit light ray sampling or path tracing.

Photon Mapping [Jen96] produces accurate caustic patterns by separating the path tracing step from a cached surface sample integration step; however this method also incurs a high computational simulation cost. Bidirectional path tracing [LW93] and Metropolis light transport [VG97] both attempt to model caustics without creating the systematic (blur) inaccuracy inherent in photon mapping, but instead incur noise. Hachisuka et al. [HOJ08] presented Progressive Photon Mapping which offered a more efficient and robust progressive radiance estimate. However, Progressive Photon mapping is still computationally expensive (22 hours per frame for their glass lamp example), view dependent, and scene dependent.

Ward [War94, LS98] proposed a physically-based rendering system RADIANCE, which is widely used for modeling ancient architectural scenes, but this system struggles to render caustics. Liu et al. [LDBP08] introduced *Caustic Spot Lights* for rendering caustics. They attempted to approximate the light departing an object with a parameterized optimization of ray bundles.

Devlin and Chalmers [DC01] contended the proper spectral data of original light sources was necessary to properly view the frescoes of the House of the Vettii in Pompeii. They showed that the perception of the frescoes was significantly different when illuminated by simulated authentic olive oil lamps, than when viewed under modern lighting.

Sundstedt et al. [SCM04] argued that accurately modeling the ancient Egyptian temple of Kalabsha necessitated proper illumination, including the correct location of the sun in the past, to simulate how it would have appeared in 30 B.C. Bridault-Louchez et al. advocated virtual reconstructions need to be physically and perceptually valid through accurate lighting simulations [BLLR06].

The nature of the computer display is also of major importance when visualizing cultural heritage reconstructions. Zányi et al. showed how novel high dynamic range (HDR) displays, which are 10 times darker and 30 times brighter than conventional displays, significantly affected the visualization of Byzantine icons under ancient illumination [ZCBC07]. Most recently Gonçalves et al. demonstrated that highly accurate modeling of the ancient lighting in a Roman site, including the manufacture process, the fuel (mixing salt with the olive oil) etc, together with HDR imaging have resulted in some of the most authentic lighting in virtual archaeology to date [GMMC08].

Example of early Islamic light source

Figure 1: *Early Islamic light sources are not simple, static, uniform points, and the fixtures themselves are often combinations of glass, water, fuel and flame generating subtle lighting effects.*

3. Lighting in Islamic Buildings

The Mediterranean region has long produced glass, with Syrian and Egyptian glass centers noted in particular. Production of these centers appears to have been continuous, uninterrupted in any significant way by the Islamic conquests of the seventh century CE. In fact, monumental interiors continued to be lit largely by the same techniques that are known for Byzantine buildings [LB09]. Rogers has pointed out problems in localizing the production of Islamic glass [Rog92]. Remaining examples of lamps and polycandela, located in mosques, such as the Mosque of Qayrawan [MP52] or excavated at sites such as Medina Elvira [Dod92, War98] nonetheless allow us to assume such continuities in lighting for the far west of the Islamic world with assurance for consumption, if not yet for production. The original fixtures of the 8^{th} through 10^{th} century Mosque of Córdoba appear not to have survived, so we have applied information gathered from other contemporary sites and artifacts to determine how this complex mosque interior would have been lit by these types of glass fixtures.

Early mosques had a multitude of purposes. Not only a place for prayer, a main or congregational mosque (*Masjid al-Jami'*) served as a center of political and symbolic display for power holders (in this case, the Umayyads of Spain/al-Andalus), a place for study, a social gathering place, location for judging cases, and other Islamic community functions. Therefore, simulating light properly is important to understand how these activities would have been situated and performed. Our method correctly models the downward light that would have been used for navigation, prayer, and study groups.

3.1. Lighting Materials

Early Islamic (and Byzantine) fixtures themselves are often combinations of glass, water, fuel and flame generating subtle lighting effects (see figure 1). These light sources hung either singly by using a jar lamp (see figure 2) or in a group of lamps inserted in polycandela (see figure 3).

Single Jar Lamp (Khalili Collection)

Figure 2: *Here is an example of an early Islamic light source hung singly by using a single jar lamp.*

Polycandelon (Khalili Collection)

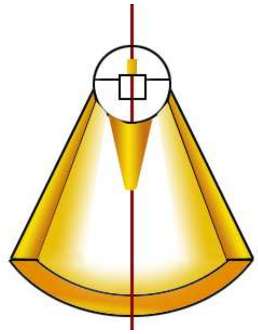
Figure 3: *Here is an example of a Polycandelon tray used to hold multiple light sources. Polycandelon were both single level and mutliple tiers.*

Based on surviving examples of jar lamps (examples in the Khalili collection, [Gol92]) and on a representation of a mosque interior from Qur'an frontispieces found in the Great Mosque of Sana'a, Yemen (for illustration, [Gra92]), we have assumed that the lateral areas of the Mosque of Córdoba would have also been lit with singly hung jar lamps from the lower arches. The lamp, suspended by three handles on chains, would have had a round body, and a funnel shaped neck, probably with a hollow glass tube secured in the center.

Down the axial nave, leading toward the mihrab niche, hung polycandela illuminating the passageway. Polycandela, fitted either in a single level or multiple tiers, are best known from earlier surviving Byzantine examples, or from the Mosque of Qayrawan. Whether single jar type or the glass inserts for the polycandelon, these lamps were filled with water and a layer of oil floating on top of it. Wicks were held in place with metal clips and/or placed within the hollow tube. Reasons of economy and safety are usually proffered as the explanations for this arrangement. Our experiments provide an important third reason: intensification of light.

4. Recreating Glass Lamps

Properly creating caustics for glass lamps requires a thorough examination of actual fixture types, varying water levels, and height positions. For our experiments, we examined three contemporary glass fixtures: a round globe, a cone shape, and a 'flat' bottomed one; three different water levels: no water, medium, and high; and three different mounting heights: ground level, 6 inches up, and 15 inches high. Our test environment consisted of two cameras and one video camera (shot straight on and from a top down angle) with a curved white seamless backdrop. Additionally, for every fixture, height, and water level we captured a 'cross-section' view (see figure 4) where we placed white paper perpendic-

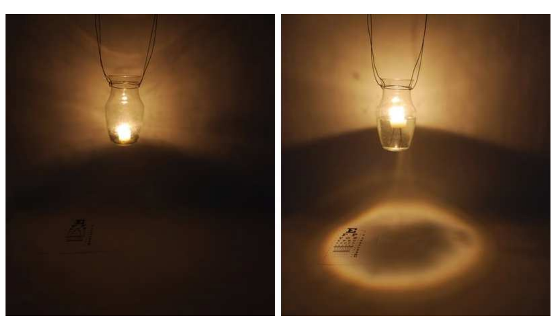


Cross Section View

Figure 4: *This diagram illustrates a cross-section view that was cast on our paper hung across the diameter of the fixture perpendicular to the camera. This shows two cones are cast in the vertical cross section. These cones will vary based on the flames' intensity and position. (The red line indicates the optical axis.)*

ular to the camera on the diameter of the glass fixtures to capture the caustic cone illuminate that was cast. Table 1 illustrates our gathered data. At every view, we hand measured the diameter and width of the circular caustic, amount of water in the fixture, height of candle, and the various distances to the cameras.

These experiments clearly show that the amount of water content placed in the glass fixture directly influences the lux of the circular caustic cast downward (see table 2). When no water filled the fixture, little light is cast downward making it more difficult to navigate, study and read (see figure 5). This result showed that not only did the water cool the glass, it yielded more direct downward light for reading and navigating inside the mosque.

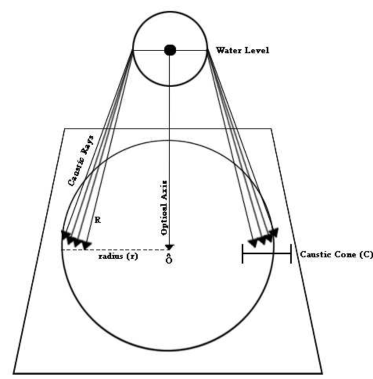


Illumination levels produced from *Caustic Cones*

Figure 5: *Having a higher water level produces an illuminate underneath the lamp fixture that facilitates navigation and reading. The fixture on the left contains no water, the fixture on the right contains a high level of water.*

4.1. Caustic Cones

Caustic Cones approximate dynamic light by utilizing video and photographic data captured from our experiments. A *Caustic Cone* is defined by a group of rays with varying intensities bundled as a cone that is radially symmetric on the optical axis O. Figure 6 demonstrates the ray casting from the glass fixture. *Caustic Cones* estimate light by utilizing video and photographic data captured from our experiments to derive a series of parameters: the caustic's radius and width, height of the fixture, amount of water, and distance to the camera. We utilize the photograph images as a start for an intensity map to parameterize a specialized ramped gradient spot light that produces the varying illuminate effect of the downward caustic pattern. This allows for a more physically accurate simulation since our method is driven from real capture data. We use these parameters to generate our virtual images. Once the parameterized light is constructed, we can adjust this light similar to a spot light in in the modeling package Maya. Parameterization allows interpolation and extrapolation of our capture data set to novel light intensities, heights, and angles for a fixed fixture geometry



Ray Diagram

Figure 6: *Ray diagram of a* Caustic Cone*. The lower rectangle represents the floor plane. The optical axis is defined by the vector from the light origin c in the ô direction*

4.2. Dynamic Flame

Our primary focus has been to properly model the downward caustic. To accomplish this goal, we needed a model of a dynamic flickering flame sources. The dynamic flame is simulated by a series of cylinders whose dimensions and rotations were derived from video of a flame similar to the method used by Devin and Chalmers [DC01] and Sundstedt et al. [SCM04]. Additionally, the flame's flicker frequency was derived from the video. We randomly applied transforms to the series of cylinders rotating 360 degrees in space. Our *Caustic Cones* method simulated the dynamic flame since our method allows for novel simulation of new illuminations from interpolating or extrapolating the intensity maps, new heights, and flame angles not captured in the experimental process. We compared our simulation results to video captured of the same fixture in our test environment simulation results to confirm its visual plausibility. The dynamic flame merely changed the parameters of the caustic cone allowing for a smooth simulation of the flickering pattern.

4.3. Caustic Cones on Uneven Surfaces

Since we simulate the downward caustic pattern by our Caustic Cone method, which in essence is a bundle of rays as a parameterized ramped gradient spot light, our simulation handles caustic patterns on uneven surfaces. The light cast by a Caustic Cone on any other (uneven) surface is just based a ray-surface intersection test. The intensity is calculated from the spot light's ray that intersects the surface. This produces skewed and appropriate caustics as the rays intersect the surface.

4.4. Combining multiple Light Sources

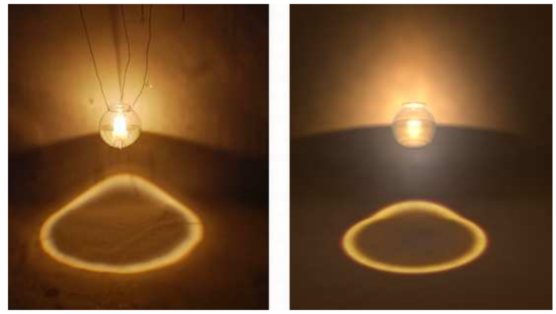
Polycandela combine multiple light sources together, arranged either in a single level or multiple tiers. Our method supports combining multiple lights together in polycandela arrangements. The final intensity is combined at the intersection of the rays on the surface points. Additionally polycandela both support and change the glass fixture's lighting pattern. Due to the polycandela's metal tray, the brightest part of the downward caustic may be diffused based on the water level in the vase from the metal. This leaves only the nearly uniform illuminate part of the caustic. Our system allows archaeologists to change parameters to test water levels to block part of the caustic and change the model of the polycandela (multiple light placement) to conduct experiments to determine proper water and light levels for the mosques.

5. Results

5.1. Validation and Rendering Times

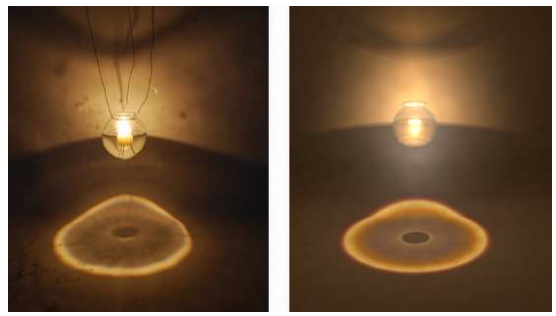
We modeled and rendered the same scene in Maya corresponding to the scene where we captured the photographs described above. Figure 7 and Figure 8 compare the downward cast caustics for both the ground truth photograph (left) to our Caustic Cone Simulation (right) for two different water levels. Our result produces a visually plausible and physically accurate result in two canonical test cases.

The cost of our render for our Caustic Cone test case was 5 secs per frame. The cost for the RADIANCE result was 23 minutes per frame. The cost for the texture map result was 20 secs per frame. Hachisuk et al. [HOJ08] presented Progressive Photon Mapping which when run on only a slightly more complex scene cost of 22 hours per frame for their glass lamp example.



Validation View 1

Figure 7: *(Left) Actual caustic pattern from high water-filled fixture. (Right) Maya rendering of similar configuration using Caustic Cones.*



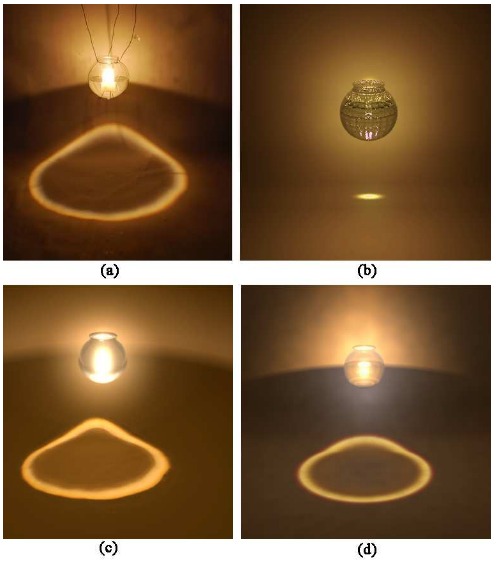
Validation View 2

Figure 8: *(Left) Actual caustic pattern from high water-filled fixture. (Right) Maya rendering of similar configuration using Caustic Cones.*

5.2. Physically Based Rendering

Various physically based renderers such as RADIANCE are widely used for modeling ancient architectural scenes; however they rarely capture the true ambiance of the environment due to subtle lighting effects. Specifically, these renderers often fail to correctly model complex caustics produced by glass fixtures, water level, and fuel sources. In Figure 9 (b) we modeled our test scene and attempted to render the caustic with RADIANCE. This example shows how Radiance poorly handled the caustics and did not produce a physically accurate render.

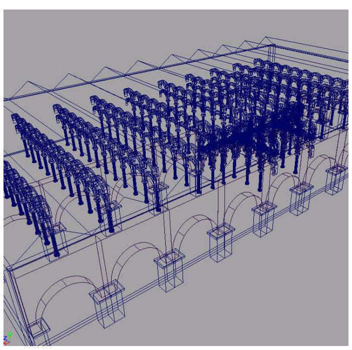
The second comparison technique (see Figure 9 (c)) uses the real data as a composite texture that was also set up as an illuminate in Maya and rendered with Mental Ray. This produces a similar caustic to the real data rotated, however, the glass fixture changes heights and is rotated, the caustic does not look realistic or physically accurate; therefore it cannot handle any new situations or any change, such as uneven geometry. On the other hand, our Caustic Cone method



Validation Comparison

Figure 9: *(a) Is a ground truth photograph, (b) Result from RADIANCE, (c) Composite Illuminate Texture Result, (d) Result from Caustic Cones. Here we illustrate that our method most accurately models the downward caustic.*

Figure 9 (d) downward caustic is more similar to the ground truth photograph Figure 9 (a).



Mosque of Cordoba Model

Figure 10: *This image shows the Mosque of Córdoba maya model we used for our renderings.*

5.3. Relighting Islamic buildings with Caustic Cones

To test our method, we modeled the 10^{th} century Mosque of Córdoba from various architectural plans and available photographs (see Figure 10). First, we modeled the Mosque of Córdoba under ambient light (see Figure 11). This lights the scene unrealistically, and does not produce a perceptually valid representation of how the mosque would appear under

Mosque of Córdoba under Ambient Light

Figure 11: *This image shows the Mosque of Córdoba rendered under simple Ambient Light showing a physically inaccurate and perceptually invalid result.*

Mosque of Córdoba under Caustic Cone Lighting

Figure 12: *This image shows the Mosque of Córdoba rendered under our Caustic Cone method producing a more perceptually valid representation.*

10^{th} century lighting conditions. We apply our Caustic Cone method to the Mosque of Córdoba model (see Figure 12 and figure 13). The resulting render produces focused light from multiple light sources in the polycandela, illuminating the axial nave passageway for navigation. Light from single jug lamps light the lateral bays hanging down from the arches. This result is more realistic and shows the best places for study and social gatherings allowing archaeologists to conduct more accurate analysis of the mosque space.

6. Conclusions

Water in the lamps helps to focus the light downwards which makes reading and navigation possible in otherwise dimly lit environments. Our *Caustic Cones* method is both more efficient and provides a more physically and perceptually accurate model than current state-of-the-art physically based renderers, some of which (such as RADIANCE) are not capable

Mosque of Córdoba under Caustic Cone Lighting

Figure 13: *This image shows a second view of the Mosque of Córdoba rendered under our Caustic Cone method producing a more perceptually valid representation.*

of accurately recreating the complex caustics anyway. Our data driven model may be readily extended to other glass fixture geometries to portray empirically valid caustics and thus to illuminate accurately 3D architectural models.

Several future directions exist for our work. First, we hope to speed up our approach even further by moving our method to the GPU to allow for real time visualization with proper illumination. Another direction would be to account for indirect lighting and use *Caustic Cones* on surfaces as indirect light sources to compute global illumination.

Overall this is the first part of a multiple part project to develop more satisfying explanations for the design genesis of the polylobed arch screens that were part of the 940CE expansion, enhancement and decoration of the mosque by al-Hakam II [Ewe68]. To fully judge our hypotheses, the lighting has to be accurately reconstructed in the mosque interior to make a perceptually valid representation for future experiments and studies.

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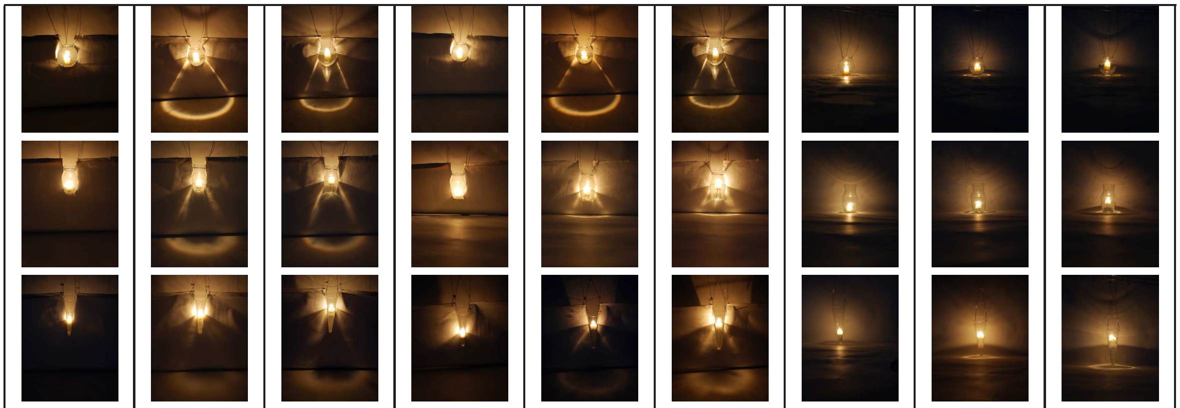
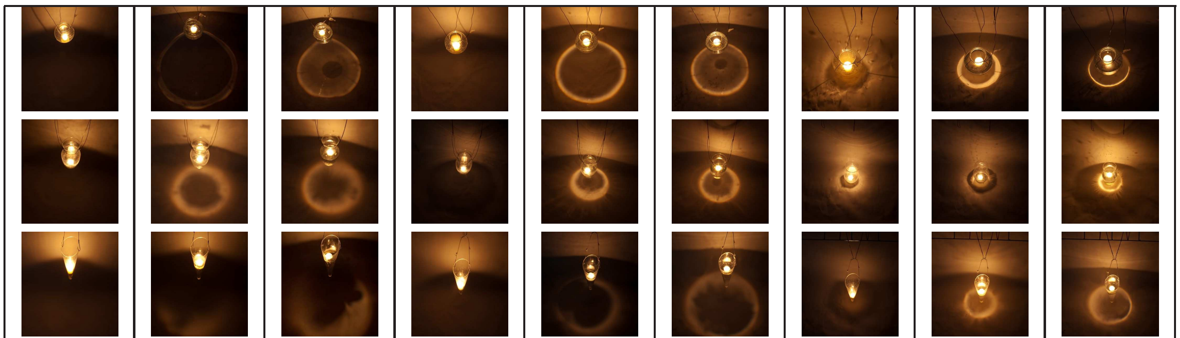


Water:L Height:H	**Water:M Height:H**	**Water:H Height:H**	**Water:L Height:M**	**Water:M Height:M**	**Water:H Height:M**	**Water:L Height:L**	**Water:M Height:L**	**Water:H Height:L**

Table 1: *Results of data collection from cross-section viewpoint experiment of 3 modern glass fixtures: round (row 1), flat (row 2), cone (row 3) at 3 different heights (low (l), medium (m), and high (h)), and 3 water levels (low (l), medium (m), and high (h)). This demonstrates how the water level affects the 'caustic cone cast'.*



Water:L Height:H	**Water:M Height:H**	**Water:H Height:H**	**Water:L Height:M**	**Water:M Height:M**	**Water:H Height:M**	**Water:L Height:L**	**Water:M Height:L**	**Water:H Height:L**

Table 2: *Results of data collection from top viewpoint experiment of 3 modern glass fixtures: round (row 1), flat (row 2), cone (row 3) at 3 different heights (low (l), medium (m), and high (h)), and 3 water levels (low (l), medium (m), and high (h)). This demonstrates how the water level affects the 'caustic cone cast'.*

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