COMPUTER-OPTIMISED SHADING DESIGN

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ABSTRACT

Computer modeling and simulation has a relatively long history in the prediction of thermal and lighting performance in buildings. As the input requirements of such analysis are quite extensive, these areas tend to be addressed computationally only in the latter stages of the design process, usually as a validation of decisions already made. However a detailed computation of incident solar radiation requires much less detailed input and has many applications much earlier in the process. Of significant importance is its potential as a tool to drive design decision-making and as a form generator in its own right.

This paper demonstrates how solar position calculations can be used to automatically generate quite complex optimised shading devices and quickly determine the solar envelope of developments given even the most stringent of overshadowing restrictions. The limitations of the precise geometric calculation of shading shape are discussed and an alternate approach to handling more complex situations using ray-tracing techniques is presented. These methodologies have been integrated into an interactive conceptual design tool called ECOTECT (http://www.ecotect.com).

INTRODUCTION

For many architects the accurate design of even basic shading devices by manual methods can be a laborious task, especially on a building with many different facades or window types that need to be considered. As a result, many projects receive at best only a cursory consideration of shading. Even with computer programs able to project shadows onto 3D building models, the design of an effective system can be an arduous process of trial and error.

However, computer-generation of optimised shading devices can significantly reduce the time and effort required on the part of the designer. With the right user interface, it's simplicity may even encourage investigative shading analysis where none would ordinarily have been attempted, or allow the assessment of several approaches to each situation.

Tools for determining the shading requirements for a window have been widely available for some time (Olgyay et al. 1957; Van den Eijk, 1965; Mazria's 1979; Markus & Morris, 1980; Etzion, 1992). Whilst a similar sun-path diagram approach has been implemented by the author, the primary focus of the methodologies presented here is the physical generation of shading geometry necessary to meet these requirements.

Previous work in the area of optimised shading design has clearly demonstrated the usefulness of a geometric approach and its application to specific cases (Arumi-Noé 1996; Kabre 1999). For the vast majority of design requirements, solutions based on a rectangular window and simple planar shading devices are quick to generate and perfectly suitable. As a result, this paper begins by presenting such a methodology.

However, complex window shapes and non-planar shading surfaces require a completely different approach and, when pursued, the solution throws open a much wider range of applications. Such a solution is presented in the second section of this paper.

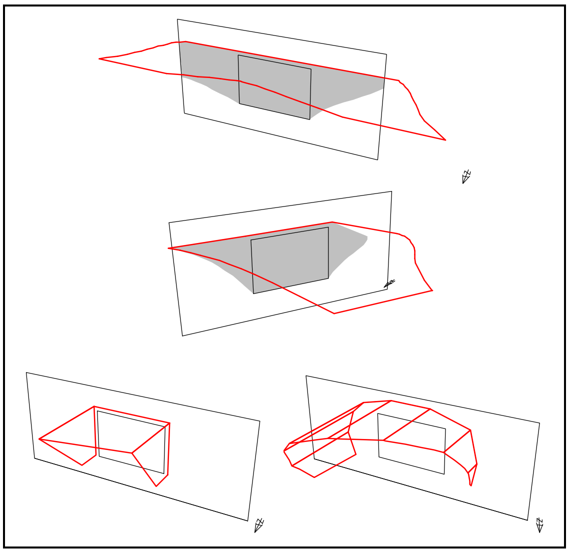


Figure 1 – Some examples of optimised shading devices generated at various orientations by the simple methods described in the first section.

1. THE SIMPLE CASE

The simplest case for the generation of a shading device involves a vertical rectangular window with one or more non-overlapping planar shading surfaces. If the designer knows the date and times for which shading is required, then the most extreme points can be found reasonably quickly using solar position tables to trigonometrically project corners of the window back towards the Sun. The points of intersection of these projections with the shading plane are then joined up to form a simple shape.

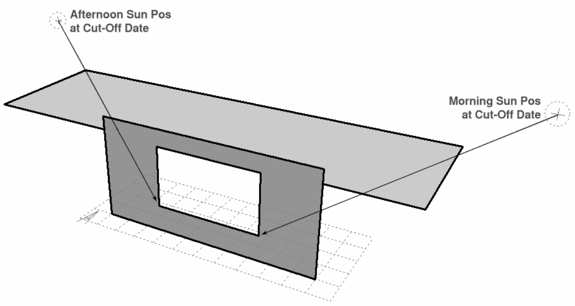


Figure 2 – Simple shading plane based on a single cut-off date and two cut-off times.

Computer-optimisation allows this process to be performed more accurately though the use of many more extreme points. This allows the resulting shape to properly accommodate the curved path of the Sun as well as analemma effects.

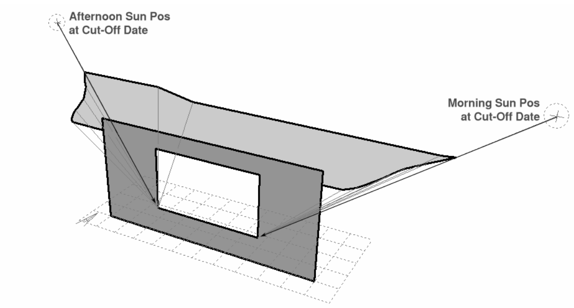


Figure 3 – Shading plane based on a single cut-off date and time range.

Unfortunately it is not simply a matter of applying a convex-hull algorithm to this set of points as there are often areas of concavity in the required shape. It is therefore the determination of which points form the limits of the shape that is the crux of this problem.

The generation of this shape is basically a four step process, based on a number of basic parameters. These parameters specify the planes that are to form the device as well as the times and dates for which shading is to be provided.

To describe the method in detail, a simple illustrative example involving a vertical rectangular window and a horizontal shading plane is used.

1. Shading Plane

The first important parameter is the plane equation of the shading surface or surfaces. The orientation and inclination is not important, other than the requirement that they be located somewhere between each window vertex and the Sun in order to actually provide shade. In this example a horizontal plane 100mm above the top of the window is used.

2. Cut-off Times

To avoid excessively large horizontal shades, morning and afternoon cut-off times are required. These are the times between which complete shading will be provided and will depend on the building type and its occupancy pattern.

For a equator-facing window, these two times define the width of the shade. Given that shading is to be provided for a range of dates throughout the year, some account must be taken of the analemma - the characteristic figure-8 shape formed by the off-axis and elliptical orbit of the Earth around the Sun.

Thus the second step is to generate the sides of the shade by plotting lines representing the path of the Sun at each of the cut-off times throughout the year. Each line is formed from the projection of the two lowest vertexes forming the window sill.

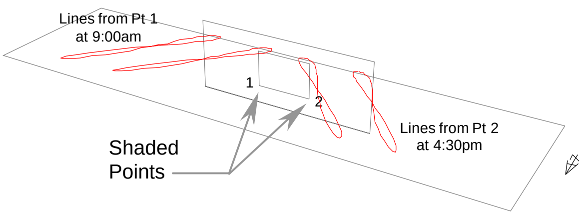


Figure 4 – Sun paths tracked onto the shading plane for the same hour throughout the year. Note the figure 8 pattern of the analemma.

For multiple surrounding shades with vertical elements each side, cut-off times can default to sunrise and sunset at the cut-off date.

3. Cut-off Date

The depth of the shade is determined by the cut-off date. This can be given as either the first or last day of the year on which complete shading is required. Full shading will therefore begin at the first shaded day, continue through summer and end on a day symmetrical about the summer solstice. Partial shading will occur outside this date range.

The third step is to generate lines representing the depth of the shade by plotting the path of the Sun through the sky at the cut-off date, starting and ending at the two cut-off times.

Two lines are formed from the projection of the two lowest vertexes forming the window sill. In fact, the two lines are exactly the same, offset by the same vector as the two sill vertexes, as shown in Figure 5.

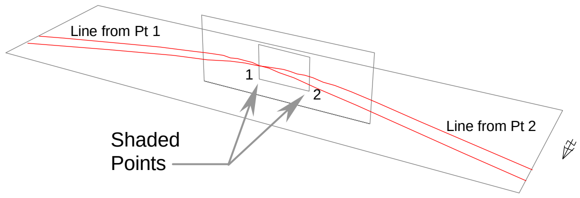


Figure 5 – Sun path tracked onto the shading plane throughout the day on the 1st of May.

The result of these first three steps are a series of intersecting lines from which the final shape can be derived. There are a number of simplifying assumptions that can be used to reduce these to a more manageable point set. These assumptions simply involve culling line segments for the range of dates and times that will not be used to define the external shape of the shade, as shown in Figure 6.

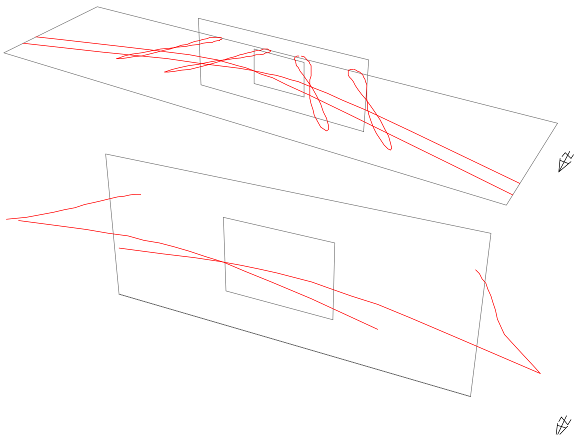
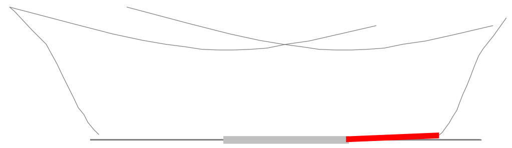
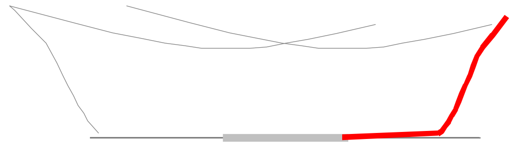


Figure 6 – The six basic sun tracks reduced to four by the application of time and date constraints.

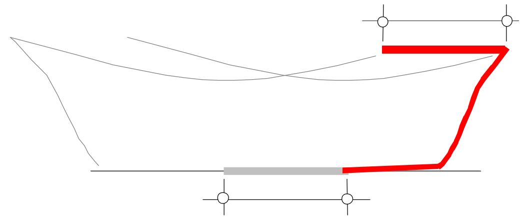
- The lines drawn in Step 2 start at the closest point to the window plane (almost always the summer solstice) and end at either the cut-off day or its symmetrical counterpart.
- Any part of the analemma line that falls behind the window plane is truncated.
- Lines need only be generated for the sill vertex closest to the Sun at each cut-off time. Thus the morning line is generated from the eastern-most vertex and the afternoon from the western-most.
- If the orientation of the window is other than towards the equator, cut-off times should be truncated such that the Sun is always on the same side of the window plane as the shade.
- After truncation, the lines in Step 3 should, start and finish at the two cut-off times.



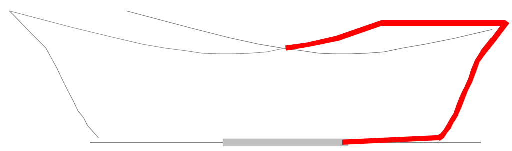
Line from intersection of top-right window vertex at morning cut-off time to start of morning analemna line.



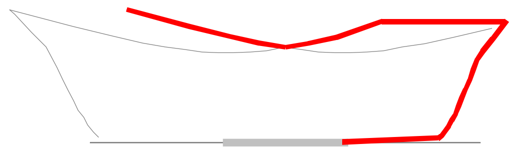
Line traced along morning analemma line.



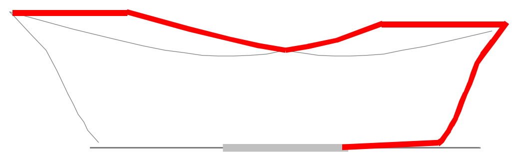
Vector added equivalent to window width.



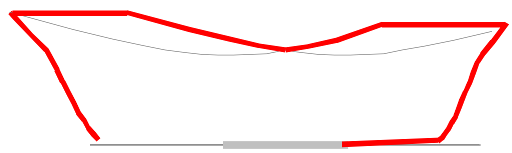
Line joined to Pt 2 cut-off date line and traced until intersection with Pt 1 line.



Line traced along rest of Pt 1 line.



Line joined to end of afternoon analemma line.



Line traced along afternoon analemma line.

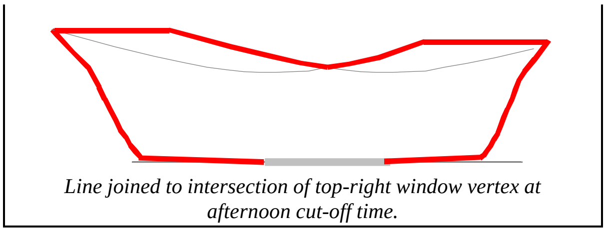


Figure 7 – How the final shape is generated from the four sun path lines.

4. Deriving the Optimum Shape

The final step is basically joining the dots, as shown in Figure 7. The main issue at this stage is determining the point of transition along the cut-off date line from Pt1 to Pt 2. The example shows the simplest case of a window facing directly north/south. However, at orientations approaching east/west, the two cut-off date lines may never intersect. Also for cut-off dates closer to the summer solstice, a different technique is required.

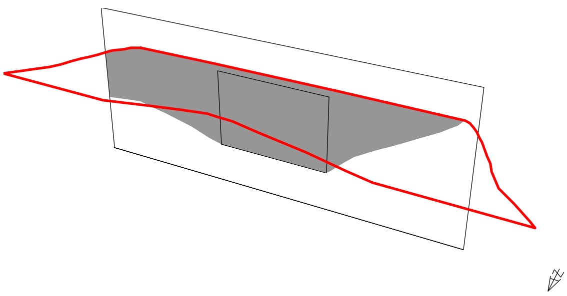


Figure 8 – The resulting shape required to shade the window between the specified cut-off dates and times.

At latitudes closer to the equator when the shading cut-off date is between the summer solstice and the equinox, the required shading device will take on a distinctly different character. In such a case, as shown in Figure 9 below, the central area of the shade will project furthest from the plane of the window.

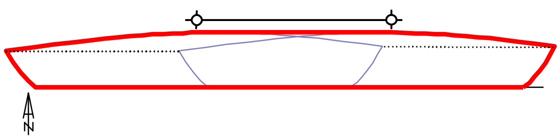


Figure 9 – The case of a cut-off date between the summer solstice and the equinox.

In these cases, the date cut-off line is traced for Pt 1 until it reaches its maximum distance from the plane of the window. At this point, tracing of the Pt 1 line is discontinued and testing of the Pt 2 line begins. Tracing recommences when the Pt 2 line reaches its maximum distance from the window plane.

Extending the Simple Methodology

The same idea of tracing the position of the Sun over time can be applied to slightly more complex shading situations. For example, given a series of shading planes, cut-off lines can be traced across each plane individually and used to clip their extents, as shown in Figure 10.

For multiple overlapping planes however, this method will result in redundant shading areas unless additional geometric clipping algorithms (as yet unimplemented) are applied to each plane.

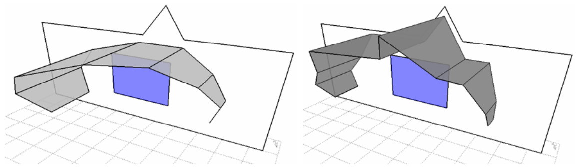


Figure 10 – Some examples of Sun-paths used to trim more complex shading devices.

Solar Envelopes

As a further extension, this same methodology can also be used to determine the solar envelope of a development given specific shading and overshadowing constraints.

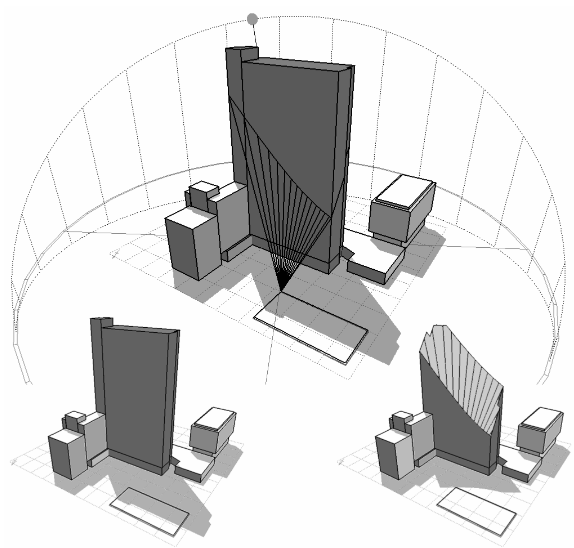


Figure 11 – Using the simple case methodology to determine the maximum development envelope given an area of restricted overshadowing.

In the example shown above, overshadowing of the rectangular area is prevented by projecting the vertex closest to the development towards the Sun throughout the day at the specified cut-off date. These projections are used to trim the development envelope. This approach to determining the solar envelope can be used for any number of vertexes or cut-off dates, making it quite flexible.

Where an entire street has a shading restriction, it may not be practical to derive the developent envelope from individual points or object vertexes. In these cases extruded planes can be used to trim the geometry.

The following example shows a plane extruded from the closest boundary of the restricted area to the development site. If overshadowing restrictions apply throught the day on a particular cut-off date, then the angle of the extrusion should be based on the lowest solar altitude occuring on that date.

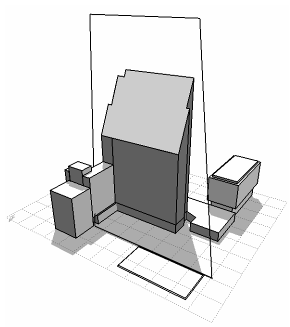


Figure 12 – Using a plane extruded at the lowest allowable solar altitude from the closest boundary to limit the development envelope.

Limitations

The simple case methodology can quickly become cumbersome when dealing with relatively complex window shapes with many vertexes or areas of polygonal concavity. More importantly, whilst the simple case method can be extended to complex shading geometry, it cannot easily be modified to include the effects of existing external obstructions around the site or self shading of the window by elements of the building itself.

To accommodate these situations, and to develop a methodology applicable to any and all cases, a new approach to the problem was considered.

2. MORE COMPLEX CASES

Unfortunately performance and effectiveness must compete against a whole range of other design considerations that face the architect when developing a shading system. Usually cost, materiality, aesthetics and even structural grid constraints will dictate the final design. As a result, it is unlikely that the optimum shading geometry will be carried through the design process and translated directly into the installed shading device.

It follows therefore, that a precise outline of the optimum shading geometry is not strictly necessary. Instead a reasonably accurate though less precise indication of the extent of shading may be equally useful, if not more useful to the designer. By displaying the relative distribution of solar intensity over a shade, the information required to balance the need for shading against other constraints is directly evident.

This potential benefits of a less precise indication of shading requirements opens the potential for ray-tracing techniques. In this case rays can be generated from the shaded surface, back through shading devices and surrounding site geometry towards the Sun. This can be done over any date and time range and allows many options in the display of solar data.

The benefits of a ray-tracing approach are many:

- It can be applied to shading geometries of any complexity, including multiple ovelapping surfaces and external obstructions.
- If linked directly to recorded or synthetic hourly solar radiation data, the results can be used to visually indicate the relative intensity of protection required over the surface of a shading device.
- Linking with solar radiation data allows for the effects of partial transparency to be considered. This includes objects with time-variant transparency such as deciduous vegetation.
- There is no limitation as to the shape or complexity of the shaded surface as it can be sampled with any level of precision.

In the implementation presented here, the result is not an outline of the required shape, but a coloured point cloud indicating the affected area and strength of shading required. To properly highlight the effect, the drawing order of points is first sorted by intensity in order to avoid the overdrawing of high intensity points by those of lower intensity, thus masking important information.

As shown immediately below, the designer can use both the location and colour of the point cloud to shape the required shading device. Areas of high solar intensity obviously require shading coverage, whereas lower intensity areas allow the designer to make a judgement call based on other constraints.

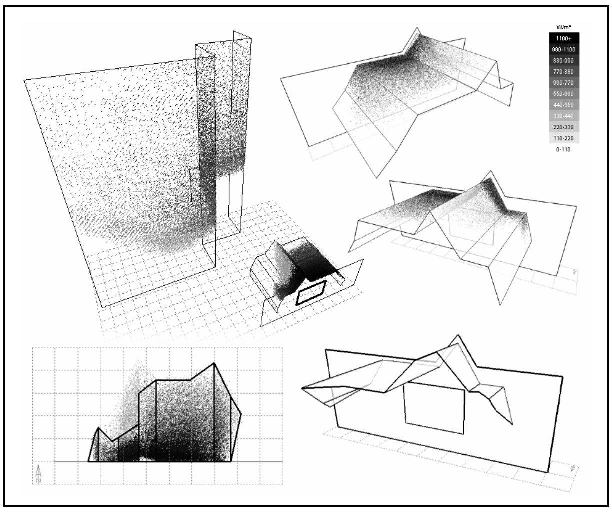
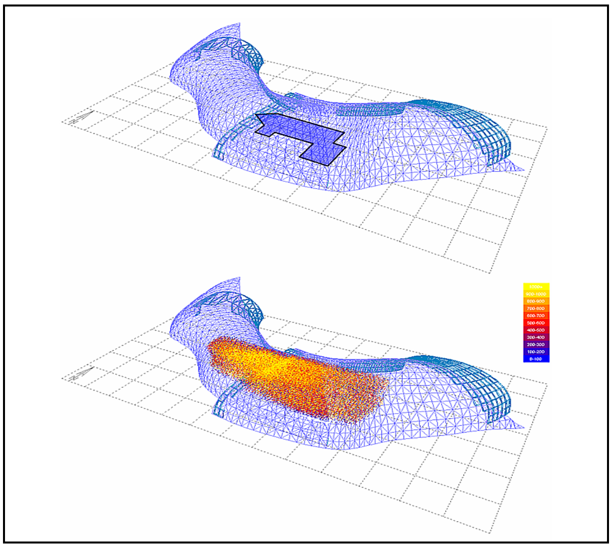


Figure 13 – An example ray-tracing analysis showing the effect of external obstructions on the distribution of solar intensity over the shading surface and the optimised shape of the device.

In the current implementation the designer shapes the shade, however work is now underway on methods to automatically derive the geometry.

This same point cloud information can also be useful when applied to the shading of a specific area of floor surface. In the example illustrated below, it is possible to quickly determine the area of the curved semi-transparent roof that shades the floor area between any range of dates and times. The extent and colour of the point cloud over the curved surface allows the designer to optimise the application of shading panels with varying transmission to provide the variable levels of protection.



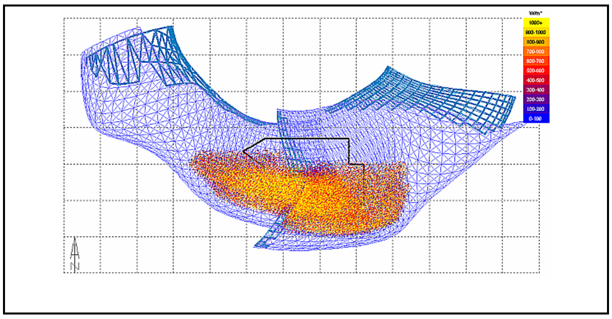


Figure 14 – Projected shading from a complex floor plan onto a complex curved shading structure.

Important Considerations

Obviously one of the important considerations in such an analysis is the source of solar radiation data. Basing the analysis on recorded radiation data for a particular year can lead to errors due to uncommon periods of cloud cover. This can be overcome to some extent by using Test Reference Year weather files or averaging radiation data over several years. However for many locations this is not always possible.

In this implementation the user can choose between actual hourly radiation values, a 30-day running average of recorded direct and diffuse values or synthetic clear-sky radiation values generated using an algorithm described by Exell (1986).

The cases shown in Figures 13 and 14 also illustrate applications with different post-processing requirements. For example, the situation in Figure 13 would be more accurate if the transmission characteristics of the window glazing were fully considered and used to moderate the relative intensity of each displayed point.

At this point in the implementation, the user has the option of including only the effects of the refractive index of the shaded glazing. Reflective, refractive and prismatic effects of transparent shading surfaces are not yet considered. This is an area for significant further work as the ray-tracing method is suitable for adaption to accommodate such effects.

CONCLUSION

Whilst there has been significant previous work in determination of shading requirements and, to a lesser extent on the computational generation of shading devices to meet those requirements, the use of computer-base shading design is not widespread within the building design industry. Previous work by the author has also focused on the assessment of shading effectiveness, whereas the aim of this work has been to implement methods of shade generation.

The work has shown that, whilst it is possible to derive the precise shape of an optimised shading device for relatively simple cases, a more generally applicable though less precise approach can provide as much, if not more information useful to the designer. Furthermore, the less precise approach can accommodate many other considerations such as external obstructions, variable transparency and time-based phenomemon that are not possible using strictly geometric solutions.

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