Tricks of the light

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Two men enter the darkened stage, apparently carrying a thick slab of badly made glass, like the stuff in the windows of old houses that turns the world outside wobbly. They hold it up, and computer scientist Mark Pauly shines a torch at it. The crowd in this Parisian auditorium gasps and then breaks into spontaneous applause.

For there on the screen behind, conjured out of this piece of near-featureless material – not glass, in fact, but transparent acrylic plastic (Perspex) – is a projected image of Alan Turing, the computer pioneer whose centenary is celebrated this year. Every thread of his thick tweed jacket is picked out in light and shadow. But where is the image coming from? It can only be the transparent slab, but there seems to be nothing there to produce it, nothing but a slightly uneven surface.

An image of Alan Turing conjured from light passing through a slab of Perspex at the Advances in Architectural Geometry conference in Paris, September 2012.

This image is made from rays refracted, folded and focused by the slightly uneven surface of the acrylic block. It's similar to the filigree of bright bands seen on the bottom of a swimming pool in the sunlight, called a caustic and caused by the way the wavy surface refracts and focuses light. Caustics are familiar enough, but they never looked like this before. Those made by sunlight shining through an empty glass are a random mass of cusps and squiggles. Pauly, a specialist in 'computational geometry' at the École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland, and his colleagues have found a way to mould and manipulate these patterns to generate any image they want, by calculating what the profile of a transparent plate needs to look like in order to marshal the light (see lgg.epfl.ch/caustics). They believe that this technique will be used by architects to create windows that are at the same time cryptic projectors, summoning ghostly images from sunlight.

The team are mostly interested in architectural applications: windows that create pictures purely for the aesthetic appeal. Pauly has teamed up with Philippe Bompas, an architect with Paris company RFR, and Austrian architectural geometry company Evolute to commercialise these "caustic windows”.

But conjuring with caustics could have a wide range of practical uses. It could provide an eye-catching form of advertising – imagine, say, a bank of ‘windows’ in a shop display or corporate atrium, each of which produces a well-defined caustic logo at different times of day while the others mutate in weird and wonderful ways. These “freeform lenses”, as others are calling them, could be used to cast a pre-defined pattern of bright and dim light from a single bulb, without light-wasting masks or filters. Other researchers working on the same problem suggest that, because these transparent surfaces require high-precision fabrication, they could supply an almost unforgeable watermark for security applications, for example in credit cards or plastic bank notes.

Since caustics can be made by reflection as well as refraction, it’s even possible that smart, shape-changing mirrors like those already used in astronomy to correct for the distorting effect of the atmosphere might be adapted to produce moving images from caustics – in other words, a new form of movie projection.

Burning light

The word *caustic* in optics shares the same origin as the more familiar, colloquial usage, for example in caustic remarks or caustic soda. It stems from the Greek word *kaustikos*, ‘capable of burning’, alluding here to the way that focused light can set objects on fire. Archimedes is said by the historian Plutarch to have used large mirrors to focus sunlight onto the ships of the Romans besieging his home city of Syracuse, setting them alight – a feat that modern experiments have shown to be highly unlikely.

Sunlight can be concentrated into bright patches either by using mirrors to reflect it or transparent lenses to refract it. A convex lens like a magnifying glass can focus all the incident light into a single bright spot at the so-called focal point a certain distance from the lens. But transparent surfaces of other shapes – a drinking glass, say, or the wavy surface of water – may marshal the light into more complex shapes, such as lines and cusps. These are the caustics. The effect is particularly familiar when sunlight passes into a swimming pool and is focused into a web of bright lines on the bottom, which constantly shifts as the waves alter the topography of the water’s surface. A similar array of shimmering bright threads may be produced in the light reflected from the water, as can be seen when it falls on the underside of bridges or on nearby walls.

Caustics caused by refraction (above) and reflection (below).

The possibility of using caustics and related concentrations of reflected light to create light from art seems to have been recognized by ancient Chinese metalsmiths of the Han Dynasty, around 2000 years ago. They made 'magic mirrors' consisting of disks of cast bronze with a smooth, reflective and slightly convex surface on one side and a picture or Chinese characters embossed on the other. When bright sunlight shines off the reflective side, the reflection shows a projected image of that on the reverse side, as though the mirror has become transparent. Such mirrors still exist, particularly those made in Japan (where they are known as *makyoh*, 'wonderful mirror') when the art was transmitted there, but the secret of how they were made has been lost. William Bragg figured out in 1932 the basic principle of how these devices work, although the essence of the explanation had been given already by a Chinese scholar called Shen Gua in an essay written in 1086. The mirror surface is not in fact perfectly smooth, but contains a very shallow replica of the image on the reverse side, too slight to be noticed by eye. It is produced by the small stresses experienced by the metal during fabrication, which causes the mirror surface to bulge in response to differences in thickness created by the relief of the embossed image. In 2006 physicist Michael Berry of the University of Bristol explained in detail the optical physics of how the images are produced (M. V. Berry, *Eur. J. Phys.* **27**, 109-118 (2006)).

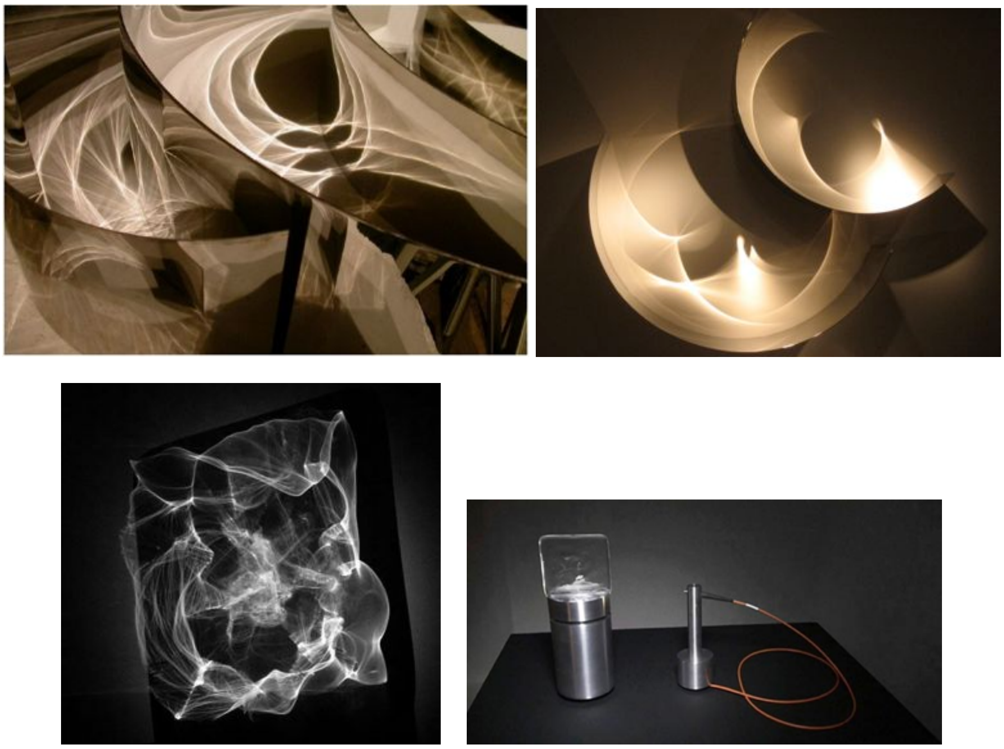
The image cast by a modern replica of a Chinese 'magic mirror'

These magic-mirror images are not exactly caustics themselves. "Caustics are surfaces in space, captured as lines on screens, onto which light is sharply focused", explains Berry. "In the magic mirror only one ray strikes the screen at each point, and it corresponds to one point on the surface of the object. When there are caustics, more than one ray strikes each point of the surface, and the caustics are the lines separating regions hit by different numbers of rays." So the light from magic mirrors is not focused. "This explains why the screen can be at any distance from the magic mirror within a wide range", says Berry.

Contemporary designers have generally used these reflections from surfaces only by happy accident. They are thrown onto surrounding surfaces from metal sheets that are curved or have uncontrolled bumpiness. The resulting play of light can be seen, for example, around the Walt Disney Concert Hall in Los Angeles designed by Frank Gehry, which has Gehry's trademark intersecting curved surfaces clad in stainless steel, like the better known Guggenheim Museum in Bilbao. The effect is particularly strong around the hall's Founders Room, where the steel was initially polished. In fact these bright reflections from the concave surfaces posed problems of glare for surrounding apartments, and even focused the sunlight into hotspots on the nearby pavements, forcing the designers to reduce reflection by lightly sanding the steel panels. The same problem has been found in rather dramatic form for the mirrored, concave façade of the Vdara Hotel in Las Vegas, which has reportedly thrown spots of focused light onto the ground that are bright enough to burn sunbathers by the pool in front of the hotel – media reports have revelled in the image of a "death ray".

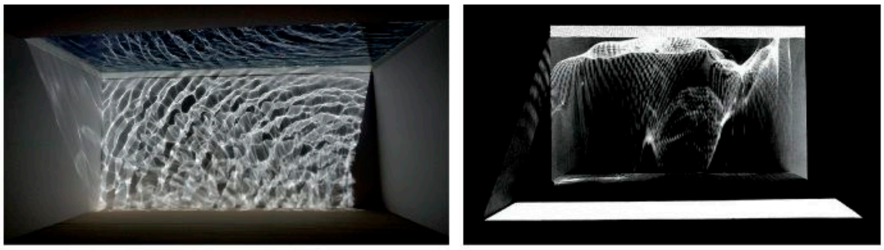
The Founders Room at the Walt Disney Concert Hall, Los Angeles, designed by Frank Gehry.

Striking caustic patterns created by refraction rather than reflection have been produced by structures that use glass cast with uneven, rippled surfaces – for example, in the glass façade of the Holt Renfrew department store in Ottawa, or the glass benches and tables of Japanese designer Tokujin Yoshioka. Since the 1960s the French kinetic artist Julio Le Parc has summoned spectacular dynamic displays of caustics from light shone onto sculptures of Plexiglass plates, cubes and prisms. Some of the most deliberate use of caustics has been made by the American sculptor Suzanne Redstone, who uses stainless-steel sheets to reflect light in arresting forms. Melbourne-based artist Nina Sellars has also used caustics for her art installation *Lumen*, devised while she was artist in residence with the Seattle-based Pilchuck Glass School. Developed with the assistance of the Laser Physics Centre at the Australian National University in Melbourne, *Lumen* uses a fibre-optic light source to project caustics from an irregular, rotating block of glass, producing an intricate, constantly changing image that Sellars calls “a poetic exploration of light in relation to the microscopic study of cells”.



Caustic art: (*top)* Suzanne Redstone uses polished metal to throw light onto surfaces; (*bottom*) A fibre-optic light source produces caustics as it passes through a glass block in Nina Sellars’ *Lumen*.

Philippe Bompas of the Paris-based architectural design company RFR was fascinated by some of these inadvertent caustic light-shows, and in the late 1990s he began to experiment with the intentional manipulation of reflective caustics to generate striking plays of light. He made small scale models of ‘light rooms’ in which a wavy mirror of polished stainless-steel throws sunlight down into the chamber below through a skylight covered with a grid-like screen that breaks up the caustics into spots and stripes, giving their projection an almost fabric-like appearance.



Caustics and related light patterns in design. Clockwise from top left: glass panels in the Holt Renfrew store in Ottawa; a glass bench by designer Tokujin Yoshioka; and two 'Light Room Experiments' by Philippe Bompas of RFR.

The basic caustics here are, however, still rather random and uncontrolled. Bompas was therefore delighted to learn that others were thinking of manipulating them in a more rational and precise way. When RFR was involved in a collaboration with the Austrian architectural geometry company Evolute in Vienna, Bompas heard from Evolute's Michael Eigensatz that Pauly, Eigensatz's former PhD supervisor, and his colleagues Thomas Kiser and Minh Man Nguyen at EPFL were investigating if caustics can be *designed*. They got in touch. "We all got very excited about potential applications in architecture and decided to collaborate on this topic", says Pauly.

Crest of a wave

The patterns that the team make are, strictly speaking, not wholly caustics. Much of the image is made up of light reflected or refracted in the same manner as the magic mirrors – although some genuine caustics, where the light is 'folded', do lace through the patterns too. Making these light pictures is essentially a matter of figuring out how the refracting or reflecting surface must be shaped to direct the light where it is needed.

This is a so-called inverse problem: one has to work back from an effect to deduce the structure that caused it. It's a familiar challenge in science: geophysicists, for example, try to use observations of seismic waves travelling and scattered through the Earth to figure out the density and composition of the planet's interior.

The researchers reasoned like this. They want to mould a uniform field of incoming light into a particular two-dimensional image in which some regions are relatively brighter and some darker, owing to the focusing of light either by reflection from a shaped mirror surface or refraction through a sheet of glass with a particular profile. Where the target image is brighter, light has to be collected from a larger area of the surface and focused into that space. The researchers divided the incoming light field, the mirror surface (for reflective caustics) and the light field of the target image into a grid of pixels, and then adjusted the pixel sizes in the mirror grid to reflect the amount of light that must be captured and directed onto each pixel in the target. Given this regridded surface, it's then not so hard to calculate the surface shape necessary to direct all the light from each pixel onto the corresponding pixel of the image. The same applies for refractive projection, where one calculates the necessary thickness of a glass plate. In effect this becomes a kind of bespoke, bumpy lens with many different focal points, which may be more or less in focus at the position of the surface on which the image falls. Only at that point will the correct caustic pattern be created – if the screen is moved further away, there's a quite different pattern, which won't necessarily resemble the target image at all.

What surprised Pauly and colleagues, however, was that when they did this calculation for a typical target image – a monochrome photo, say – the surface of the mirror or glass plate needed to make it was surprisingly flat and smooth. You'd never guess, simply by looking at it, what the target image will be, nor that it would be capable of producing any sharp contrasts of light and dark at all.

That was worrying. If the caustic generator is so featureless, can it really produce an image with any detail? And would even tiny errors in fabrication create big distortions in the image?

The only answer was to try and see. The team decided at first to make a reflective caustic, by using standard computer-controlled milling techniques to shape a slab of aluminium. They chose as their target a monochrome version of the famous engraving of a tidal wave by the nineteenth-century Japanese printmaker Katsushika Hokusai, *The Great Wave off Kanagawa*. When the slab emerged from the milling machine, looking as though it had just suffered a few small dents like the bashed side panel of a car, it was hard to be optimistic.

And indeed, when the researchers shone a flashlight onto the surface, the reflection didn't look too promising. One could just about make out the bright and dark regions of the image, but it could be almost anything. However, that was before the metal was polished. When they did the same thing with the shiny surface, they were astonished: it wasn't hard to make out all the tendrils and flecks of the breaking wave. This was going to work.

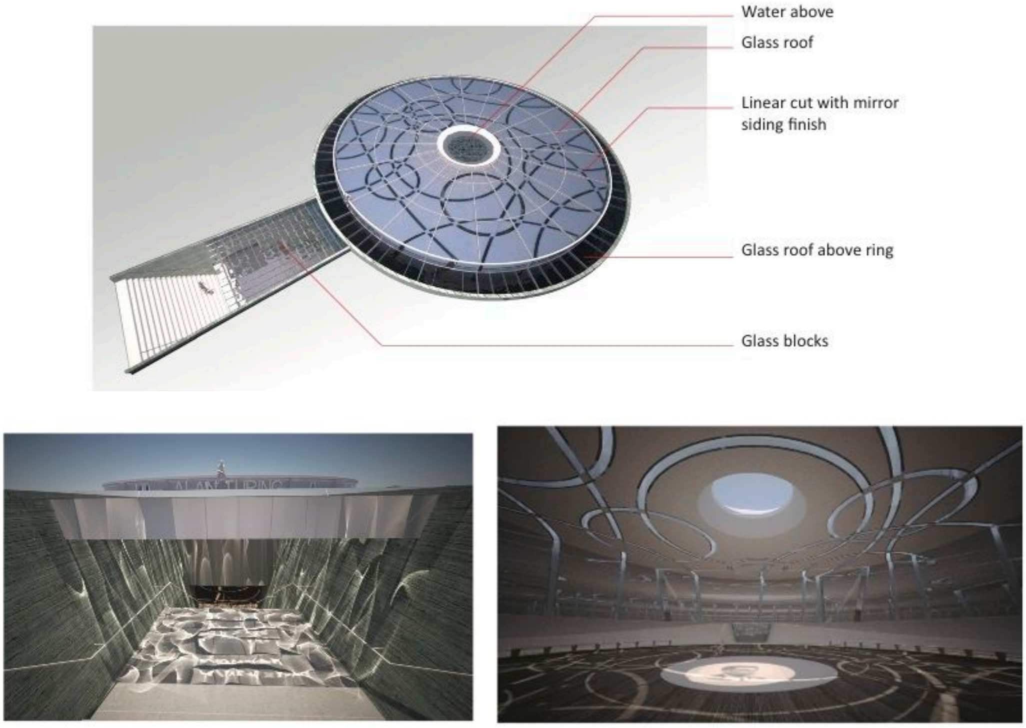
The target image (top left), the aluminium mirror (top middle), and the reflective caustic from the polished version.

Now it was time to go for broke: to make a large, transparent plate that could generate a high-resolution image. The researchers chose as their target a photo of Alan Turing, given that this year is the centenary of the birth of this pioneer of computer science. They decided to cast the plate in transparent, polished acrylic, which is easier to work with than glass. Pauly and Eigensatz demonstrated their ‘Turing plate’ in Paris at the ‘Advances in Architectural Geometry’ meeting in Paris in September, showing just how much detail can be captured despite the lack of strong contrasts of surface topography.

“Incredible detail can be achieved even with very crude production methods like standard milling”, says Pauly. “This is crucial for cost-effective application to architecture or art installations.”

But he admits that he still doesn’t fully understand why it works so well. “It might be that this robustness in the face of manufacturing error is inherent to the problem, or that it’s a feature of our particular way of computing the surface”, he says. “We’re still puzzled why it works so well.”

To illustrate the potential of the method for architecture, Bompas has designed a Turing Memorial building in which a large Turing portrait is cast onto the floor of the main exhibition hall from a window in the centre of the ceiling. The hall is reached from a set of entrance steps over which patterned glass casts a complex web of more random caustics that shift gradually as the sun moves. It’s not clear that the design will ever get built, but the computer simulations alone show how arresting it would look.



The Turing Memorial designed by Philippe Bompas. The entrance is wreathed in disorderly caustics from overhead glass blocks (*bottom left*), while the main hall has an image of Turing at the centre cast by the window above (*bottom right*).

Freeform lensing

Bompas, Pauly and colleagues aren’t alone in believing that light can be sculpted this way. Wojciech Jarosz at the Disney Research laboratory in Zurich, Switzerland, collaborating with computer graphics specialist Tim Weyrich of

University College London and others, has created images by milling the surface of a glass plate into a series of curved patches that act like little lenses, making it look a little like a fly's compound eye. When light passes through the plate, each patch directs a fuzzy ellipse of light onto a screen, and the overlapping of these patches produces a target image. (These aren't true caustics either, although there's some confusion stemming from the fact that in computer graphics any such focusing of rays tends to be called a 'caustic', whereas caustics in the strict optical sense are called 'folds'.) The crispness of the image depends on how small the patches are. But because each patch has to be individually milled to shape, the fabrication process can be very slow, limiting the resolution of the image. So far Jarosz and colleagues have made plates 10 cm square, each with over a thousand patches, but these can take up to three days to mill with a commercial engraving tool and still produce only somewhat fuzzy or pixellated images (see http://www.newscientist.com/article/dn20280-engraved-plastic-panel-casts-image-in-light-and-shade.html). They think there could be applications of their method such as transparent security 'windows' on credit cards, analogous to the holograms they contain at present, which would be very hard to forge.

The experiment (*top*), target image (*lower left*) and experimental result (*lower right*) for the caustic imaging achieved in the Zurich Disney Research lab.

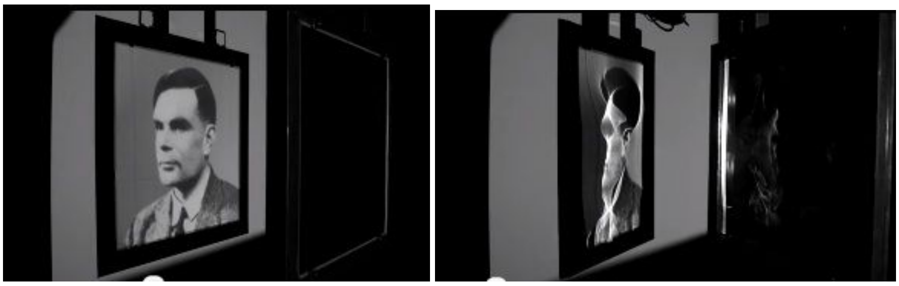
In contrast to this approach, says Pauly, "our surface is smooth, which is very important for the visual quality of both the surface and the image, has significant advantages for fabrication in glass, and can support true caustics." The Disney approach is also limited by the fact that more detail can be reproduced in the bright parts of the image than in the dark parts. However, the differences in the quality of the image could well be a matter of taste. "Architects would probably choose depending on whether they want accuracy, in which case our method is better, or the 'artsy' effect of the organic shapes of the caustic artefacts in Pauly's method and the more organic appearance of the refractor itself", says Weyrich.

This isn't the only competition. At the Fraunhofer Institute for Technical and Commercial Mathematics in Kaiserslautern, Germany, Norbert Siedow and his coworkers are developing what they call 'freeform lenses' that similarly organize incident light into an arbitrarily defined distribution of light and dark. Siedow's team has developed an algorithm that in just a few seconds can solve the inverse problem to calculate what shape of 'lens' is needed to produce a target image. So far their results are all just theoretical, but they think that as well as uses in advertising and graphic art these lenses might be valuable for lighting technology. Imagine, for example, that you want to illuminate a room unevenly – to cast patches of light and dark in different places, perhaps with smoothly graded boundaries between them. Placing a mask over the light source is one option, although not only does this make smooth intensity changes difficult but it wastes a fair bit of the light and energy from the source. A freeform lens, meanwhile, could make appropriate use of all the incident light. "One of the main ideas of freeform optics is to conserve light and energy, to bring all the light to the place where it is needed without any wastage", says Siedow. This sort of patchy lighting could be useful in museums, theatres and even for domestic interior design – your general illumination and spotlights or reading lights could all come from a single source. Such light-sculpting might also be valuable for car headlights, Siedow says, providing good illumination of the road while reducing glare for other drivers.

"The field of freeform optics is growing very rapidly", says Miguel Alonso of the Institute of Optics at the University of Rochester in New York. "New fabrication technologies have emerged that allow more versatile lens designs, which in turn lead to better, more compact systems for imaging and illumination." Quite aside from possible applications, however, the images that can be generated by this control of light have an intrinsic aesthetic appeal. "I admire the ingenuity and the beauty of these schemes", says Michael Berry.

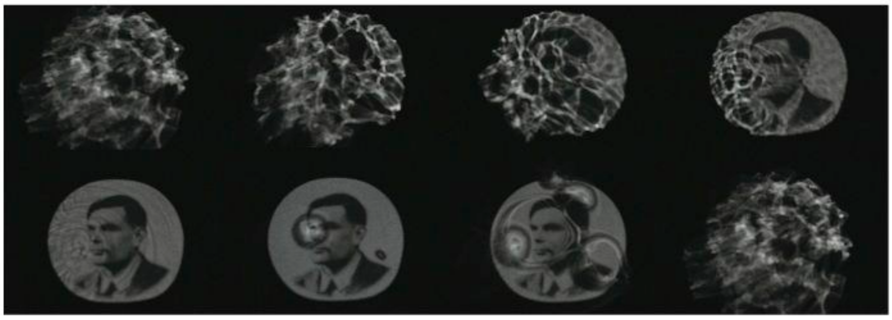
Play of light

The projected 'caustic' images change their shape depending on how close the 'lens' and screen are, and on the angle of incident light. That was clear when Pauly and Eigensatz demonstrated their 'Turing plate' in Paris: as the plate was tilted, Turing's face first became deformed into a sort of grotesque gnome before breaking up entirely into random cusps and lines.



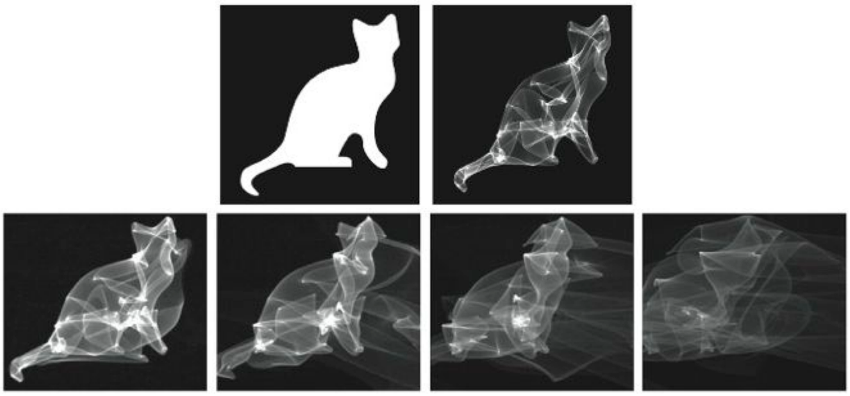
Turing breakdown: how the caustic image evolves as the plate is rotated.

Such effects might be harnessed for aesthetic effect. There would be something captivating about watching an image or slogan come into focus as the sun reaches a particular place in the sky. Bompas proposes placing a water pool above his Turing Window, so that the ruffling of wind or the ripples from raindrops make the projected image dissolve into chaos – and then reform as the water settles again.



Turing drops: a simulation of how wind or rain disturbing the water pool on the roof the Turing Memorial will disrupt the image cast on the floor.

The 'folded' appearance of true caustics can also be toyed with for aesthetic effect – Pauly and colleagues have computed refractive surfaces that will pick out a silhouette filled in with a lively pattern of seemingly random folds and pleats of light.



Caustic cat: making a silhouette (*top left*) out of caustics (*top right*), and how rotation unfolds (*lower*).

So the manufacturing process works for acrylic – but can it be done in glass, as architectural engineers might demand? Pauly is confident that it can. "We'll do some glass milling soon, and also glass casting with a mould", he says. "One manufacturer was very confident that glass milling would work." But he adds that even in acrylic there might be applications in architecture, if it can be protected from its tendency to degrade in ultraviolet light. Pauly says that already he may have some architectural clients, but can't give names at such an early stage in the negotiations.

Pauly says that one of the aspects that appealed to him was how the projected image changes as the light source or projecting surface move. But might it be possible to take this even further and generate genuine 'moving images' – caustic movies, as it were? The idea isn't implausible in principle. After all, mirrors with computer-controlled , precisely reconfigurable surfaces are already made for astronomy, where these 'adaptive optics' systems are used to compensate for distortions of the incoming light produced by fluctuations of the earth’s atmosphere. “I think something like this should be possible with a flexible membrane”, says Pauly, “but it might be hard to manufacture and control. One could also think of several objects interacting – that is, overlaying the caustic patterns to create moving images. I think the possibilities are really endless and this is what makes this project so exciting.”