Did Jan van Eyck use an optical projector to render one of the most famous paintings of the early Renaissance? Supporters of the “projection theory” have suggested that the artist built the projector by reversing the convex mirror depicted in the painting itself. The author of this article arrives at a different conclusion by use of geometrical optical analysis.

The contemporary painter David Hockney, in seeking to explain an apparent increase in realism in European art around 1420, recently proposed that some early Renaissance painters employed optical devices to project images onto their canvases or other supports, which they then traced or painted over. Hockney received technical assistance on his theory from thin-film physicist Charles Falco. The two adduce as central evidence Jan van Eyck’s (1395–1441) “Portrait of Arnolfini and His Wife” (1434).

To test their claim, I applied optical as well as two- and three-dimensional (3D) image analysis techniques to the Arnolfini double portrait. The masterpiece is an ideal test case, in part because it has been the focus of extensive scholarship and analysis. Hockney and Falco have also referred to the painting in virtually every public lecture, magazine article, television or radio interview and Web site posting regarding their recent work, as well as in Hockney’s BBC documentary. If the Hockney theory should fail in this case, then surely it would come under strong doubt.

Figure 1. Jan van Eyck, “Portrait of Arnolfini and His Wife” (1434), oil on panel, 81.8 x 59.7 cm.
Hockney’s optical projection theory posits that as early as 1420, some painters employed optical devices in the creation of their works. Specifically, he suggests they used a primitive camera obscura in which focusing was achieved by a concave mirror. (He theorizes that much later, around 1600, glass lenses were used instead of mirrors.) The artist would project a real inverted image of the scene or part of it onto the canvas and either trace its contours or perhaps even paint directly\(^1,2\) although as Hockney himself admits, it is quite difficult to paint under optical projections. Most of my 2D and 3D analyses address shape and geometry, and apply equally to images traced or painted directly under projection; for this reason, I will not distinguish between the two methods. I defer to the work cited in Ref. 8 for an analysis of color and lighting in which this distinction is relevant.

Testing the theory

Hockney and Falco have proposed that van Eyck used the famous convex mirror depicted in the Arnolfini portrait, or a similar one, as the projection mirror in a primitive camera obscura. Three of many quotations will suffice. Charles Falco: “… Remember in those days, the back side of a mirror wasn’t blackened, they just silvered the bottom of a globe of blown glass and sliced out the circular segment—you’d have a concave mirror, and in fact the very same [Arnolfini] mirror as the one that may well have been used to construct this image.”\(^9\) David Hockney: “If you were to reverse the silvering, and then turn it round, this would be all the optical equipment you would need for the meticulous and natural-looking detail in the picture… Van Eyck could have hung the panel upside down next to the viewing hole and painted it directly, following the forms he could see on the surface.”\(^4\) Finally: “Van Eyck placed a convex mirror at the very center of this [Arnolfini] masterpiece, the very mirror which, turned around, he may well have used to construct the image.”\(^5\)

I note in passing that there are numerous engineering difficulties in the creation and silvering implied by the claim, and that, to my knowledge, there is no contemporary documentary evidence that such convex blown glass mirrors were turned around and used for projection. To address the claim, I estimated and compared the focal length of a concave mirror putatively used for projection, \(f_p\), and the mirror depicted in the painting itself, \(f_p\).

The method for estimating \(f_p\) relies on determining the angle of view of objects of known or assumed size and distance as well as measured image sizes in the painting, a standard method employed by Hockney and Falco in an analysis of another painting.\(^6\) The visual angle \(\theta\) at the principal point of the imaging concave mirror subtended by an object of estimated or known dimension, \(H\), and the corresponding distance across the scene obey:

\[
\tan(\theta/2) = 1/2 \times \frac{[\text{distance across scene at } H]}{H}. \quad (1)
\]

I applied the Hockney and Falco method to eight objects and their associated distances in the painting (heights of Arnolfini, his wife, window casement, window bench, rear seat, bed, floor-to-hand, diameter of mirror glass, length of Arnolfini’s sandals), using whenever possible sizes given in the scholarly literature, such as the diameter of the mirror glass.\(^7\) My result is \(f_p = 61 \pm 8\) cm. For reasons that will be clear below, I shall call this

Editor's Note

In July 2000, Optics & Photonics News published “Optical Insights Into Renaissance Art,” an article by artist David Hockney and University of Arizona optical sciences professor Charles Falco. The photographic quality of some Renaissance paintings had inspired the two to explore the possibility that some Old Masters relied on optical aids. “We have discovered a variety of scientific evidence that strongly supports and extends” this theory, the authors wrote. In the intervening years, the subject has generated a great deal of interest and debate. Here, Ricoh Innovations scientist David Stork challenges the theory. Readers are invited to share their thoughts on the topic by sending letters to the editor (opn@osa.org).
a "long" focal length. Incidentally, this value is within 11 percent of a focal length computed by Hockney and Falco of a purported projection mirror on a different Renaissance painting. 6 My focal length is a bit less than the diagonal measure of the Arnolfini portrait (81.8 x 59.7 cm) and as such agrees with the results of Carleton, who concluded that the painting evidences a slight 'wide angle' perspective. 10,11 It would be possible to use more sophisticated methods to estimate the focal length, such as propagating Gaussian error models, 12 but as will be seen shortly, my result is more than sufficient for the comparison at hand.

I then estimated the focal length of the convex mirror depicted in the painting, \( f_{\text{gd}} \), by two semi-independent methods. The first was to use the assumed or inferred object sizes and distances, as above, then the lens equation, for a negative lens or convex mirror,

\[
\frac{1}{d_o} + \frac{1}{d_i} = -\frac{1}{f_{\text{gd}}} \tag{2}
\]

where \( d_o \) and \( d_i \) are the object and image distances and \( d_o/d_i \) is the magnification. 11 Each object subtends a visual angle at the principal point of the concave projection lens, as does its corresponding erect virtual image in the convex mirror. Simple geometric analysis thus yielded an estimate of \( f_{\text{gd}} \). From four such estimates, I found \( f_{\text{gd}} = 17 \pm 4 \text{ cm} \), which I call a "short" focal length. Of course, by convention, this focal length is negative for a convex mirror and positive when the mirror is turned around; because there is no ambiguity of sign, I reported the focal length as positive.

A second method of estimating the focal length is more holistic, global and image-based. Here, following Criminisi, Kemp and Kang, 13 I modeled mathematically the optics of the convex mirror depicted in the painting and then adjusted the model's radius of curvature to undo the spherical aberration evident in the image in the painting (see Fig. 2). The "best" such radius of curvature is the one that yields the least distorted view from the convex mirror back toward Arnolfini. Of course, the image transformation is radially symmetric about the central axis. As shown at the top of Fig. 2, the transformation from position on the mirror \( r \) (as revealed in the painting) to the corrected position \( h \) on a very distant hypothetical viewing screen obeys

\[
h = \sin\left[R \cos\left(\frac{r}{2}\right)\right], \tag{3}
\]

where the overall scale in the viewing screen is irrelevant. I adjusted \( R \) to make the resulting image "good" (appear most rectilinear); for the best fit \( R \), I find \( R/D = 0.68 \).

Figure 3 shows this "best" image, as defined above. In the paraxial ray approximation, the focal length of a concave or convex mirror is simply half the radius of curvature of the sphere, that is, \( f = R/2 \) [Ref. 11]. I found in this case \( f_o = 19 \text{ cm} \).

Incidentally, since Criminisi, Kemp and Kang 13 report that even the best dewarping under a parabolic mirror assumption does not yield an acceptable image, I can reject the possibility that the mirror was parabolic. I combined the two semi-independent estimates, making natural assumptions about degrees of freedom, and concluded \( f_o = 18 \pm 4 \text{ cm} \). I am now in a position to judge the Hockney and Falco theory that the convex mirror depicted could have been used as a projection mirror. Given my estimates \( f_o = 18 \pm 4 \text{ cm} \) and \( f_p = 61 \pm 8 \text{ cm} \), I must reject their conjecture with great statistical confidence. (On the basis of a careful perspective analysis, I also find it unlikely that van Eyck created the painting as a mosaic of numerous short-focal-length "exposures."\)

**Perspective analysis of the chandelier**

Perhaps some other concave mirror was used for projection? Hockney has claimed repeatedly that the chandelier in the Arnolfini portrait must have been drawn under projection. In an interview broadcast on the CBS news show "60 Minutes," the following exchange took place. Reporter Leslie Stahl: "Hockney points to van Eyck's 'The Arnolfini Wedding.' He used to wonder, 'How did he do that chandelier?'" Hockney: "That chandelier is in perfect perspective. So how was it drawn?" Stahl: "He now thinks with a concave mirror and a pencil." 14 I addressed this claim by perspective analysis of the chandelier. If the

![Figure 2](https://example.com/image2.png)

**Figure 2.** (Top) A transverse schematic cut-away of the spherical mirror with facial diameter \( D \) and radius of curvature \( R \). (Bottom) If the convex mirror were turned around for projection, its blur circle would have diameter \( b \sim 1.6 \text{ cm} \), much too large to reveal the detail in the painting; the mirror would have to be stopped down to yield an acceptably sharp image.

![Figure 3](https://example.com/image3.png)

**Figure 3.** The image in the spherical convex mirror reversed and corrected for spherical aberration, according to Eq. 3, using the optimal value of \( R \). This represents the view from the position of the mirror back toward the room and the painter.
chandelier “is in perfect perspective” then a concave mirror might conceivably have been used since its projection would be in proper perspective. Conversely, if the chandelier is in poor perspective, it is unlikely a projection was used.

Figure 4 shows a plan of the six-armed chandelier, or lichtkroon (Dutch, for “light crown”). The dark marks indicate a few of the corresponding structures on the arms, e.g., the four decorative trefoils beneath each arm. Consider the two arms at the left in Fig. 4 (1 and 6). Imagine in the space of the room a single line linking corresponding structures, one on each arm, such as the trefoils most distant from the chandelier’s central vertical axis. Because those structures are at the same height, this constructed line is parallel to the floor. The line is also perpendicular to the vertical plane bisecting the two arms. Since these two properties hold for each line linking a pair of corresponding structures on those arms, all such lines are mutually parallel in 3D space. Similar constructed lines linking points on arms 3 and 4 are also parallel to those linking arms 1 and 6. So, too, are lines linking structures on arms 2 and 5. Under a geometrical projection, all these parallel lines should meet at a vanishing point at the height of the projection system, just as in a photograph of railroad tracks. Figure 5 shows that in fact these lines do not meet at a vanishing point.

A perspective analysis of a true projection (modern photograph) of a 15th-century four-arm lichtkroon from Barley Hall—a casting from a lichtkroon in the Museum of the Hospital of St. John in Bruges—yields good consistency: perspective lines from each of the six pairs of arms meet at reasonably well-defined vanishing points, all of which lie close to a single horizon line (see Fig. 6). The horizon line is below the chandelier, surely at the height of the camera. This “control” case verifies not only the perspective analysis method itself, but also that at least this 15th-century chandelier is reasonably symmetric.

Consider again Fig. 5. Do those haphazard perspective lines really preclude the use of projections? Perhaps the handmade chandelier deviates enough from an “ideal” shape to explain the lack of a well-defined vanishing point? I computed a weighted least-squares fit of the lines to find the “best” vanishing point, in essence inferring the location of the vanishing point had the chandelier been perfectly symmetric. Working backward, I then found how far “off” a structure was on an arm depicted in the painting: for instance, I assumed arm 6 was the “gold standard,” and asked how far a point on arm 1 had to be moved to ensure the perspective line associated with arms 1 and 6 passed through this vanishing point. This distance is a measure of the “sloppiness,” or variation, that is consistent with an optical projection. While for most of the chandelier this distance is small, Fig. 7 shows that in Arnolfini’s room, it can be as large as 10 cm, much larger than the decorative structures themselves and variations in actual 15th-century chandeliers in museum collections determined by both optical analyses and direct physical measurement.
Figure 6. A perspective analysis of a true projection (photograph) of a 15th century chandelier design from Bruges. The horizon line is below the chandelier, surely at the height of the camera.

These analyses rely on the assumption of reflection symmetry in the chandelier; I now turn to one that does not. Suppose the physical arms 5 and 6 have the same 3D shape and are related by a rotation about the vertical axis by an arbitrary angle (i.e., one not necessarily of 60 degrees). In this case, their projected images would possess geometrical invariants. Specifically, the line defined by two points on arm 5 should intersect the axis of rotation at the same point as the line defined by the corresponding points on arm 6. Note that the axis of rotation need not be vertical for this geometrical property to hold. Figure 7 shows that this implication of the projection theory is violated under the assumption that arms 5 and 6 have the same physical shape.

As before, I can infer a manufacturing tolerance consistent with an optical projection. Here, I assume arm 5 is the “gold standard” and ask how far a point on arm 6 must be moved to ensure that the constructed lines indeed meet at the vertical axis. In Arnolfini’s room, the maximum overall shift indicated is about 2 cm. Such an “error” could also arise from a rotation of arm 6 around a normal to its face by about 7 degrees.

Whether one agrees with the claim that the Arnolfini chandelier “is in perfect perspective” (and hence possibly painted under projection) thus comes down to the manufacturing tolerances one is willing to accept. Since the chandelier is unavailable for physical measurement, and since one can assume that artisans of the time time would have been able to ensure tolerances of less than a few centimeters for a wealthy patron, it seems prudent to reject—for the time being at least—the claim that the chandelier was painted under projection. A more sophisticated, but perhaps too speculative, 3D analysis could explore simultaneous allowable tolerances in rotation angle of an arm about the vertical axis; torsion within an arm; positions of the decorative structures; perspective changes with purported mirror refocusing; and inaccuracies in van Eyck’s tracing. But because there are many degrees of freedom, such an exercise could be prone to post hoc fitting of a preconceived result.

I can anticipate and rebut a number of possible objections to this perspective analysis. First, one might claim that the purported optical system was somehow improperly set up. For instance, if the concave mirror or the support or both were tipped, it would indeed be possible to create a mild anamorphism and hence shift the “horizon line” to above the chandelier. (In just such a way, to eliminate convergence of vertical lines in photographs of buildings, architectural photographers use perspective control lenses and tip their film planes.11) But the colinearity of vanishing points (along a horizon line) is preserved under such an “improper” optical setup.12,15 Because the collinearity of vanishing points in the Arnolfini painting, to the extent they can even be identified, are in fact not collinear, I can reject this objection.

Second, one might claim that the purported concave mirror possessed optical aberrations such as curvature of field, coma, distortion, spherical aberration...
or astigmatism or was otherwise poorly formed. The haphazard nature of the deviations from true perspective lines, as evident in Figs. 5-7, arises neither from such aberrations nor from poor mirror form, but surely instead from manufacturing irregularities.

Finally, one might claim that van Eyck refocused or reoriented his concave mirror as he traced the image of the chandelier, moving the mirror forward and backward, possibly tipping it and the support; Hockney and Falco have made such a claim for Lotto’s “Husband and Wife” (1523). The inconsistencies in perspective as in Fig. 8 occur even for pairs of corresponding points spanning a range of depths of a mere 5 cm, such as the pair of trefoils on arms 5 and 6 closest to the viewer—well within the depth of field of any conceivable concave mirror. The same result holds for several other pairs of corresponding points at nearly the same depths. As such, these inconsistencies cannot be attributed to van Eyck’s complicated refocusing of a concave mirror.

The historical record
After extensive reading and correspondence with historians of optics, to my knowledge there are no 15th-century records suggesting that a convex blown glass mirror was ever turned around and used as a concave mirror. More to the point, before Girolamo Cardano (1550) and the more widely known magician, playwright and optical experimenter Giambattista della Porta (c. 1558), to my knowledge there are no texts from scientists, artists, patrons or mirror-makers showing that anyone had ever seen an image of a non-luminous object (e.g., other than the sun) projected by an optical device onto a screen, much less traced or painted over it. Falco has pointed to passages from The Romance of the Rose by Guillaume de Lorris and Jean de Meun: “... Other [mirrors] make different images appear in different situations—straight, oblong, and upside down in different arrangements.... they make phantoms appear to those who look within. They even make them appear, quite alive, outside the mirror, either in water or in the air ....” This passage confirms the fact that concave mirrors existed as early as the 13th century and that people saw inverted images while looking directly at concave mirrors. However, these and other passages fail to support several important requirements of Hockney’s theory: that long-focal-length concave mirrors existed (i.e., > 40 cm)—although the technology existed to grind them—and,
more importantly, that mirrors were used to project a real inverted image onto a screen (such as a wall, paper or canvas support). Making visible projections onto a screen is harder than is indicated in The Romance of the Rose, for at least two reasons. The first is that one needs a higher quality (shape) of optical instrument to project an image onto a screen than to see an image looking into it.\textsuperscript{11} For example, it is simple to see a (deformed) inverted real image when looking at the bowl of a shiny teaspoon, but such a teaspoon cannot project an image onto a screen. The second reason is illumination.\textsuperscript{8} The projected images are much dimmer than the original scene—by a factor of roughly $A/f^2$ ($\sim 10^3$) where $A$ is the facial area of concave mirror and $f$ is its focal length. For instance, you can see a dim star reflected in a shaving mirror, but you cannot see such a star projected onto a wall because it is far too dim.

The following passage by Witelo (1230?-1275?) has been cited by Hockney’s studio assistant D. Graves. In a section titled “It is possible to set up a cylindrical or convex pyramidal mirror in such a way that one can see, in the air, things outside not in sight,” Witelo wrote: “Take a convex cylindrical mirror ... Let it be stood upright on its pedestal ...”.\textsuperscript{18} Clearly this refers to a cylindrical or a convex mirror; any suggestion that here Witelo meant instead a concave mirror is speculation.

Conclusions

I close by recalling the greatest optical scientist before Newton, Alhacen (965?-1040?), the primary influence on European optics for 500 years and the author of 16 books on optics. Even though he described optics of the eye, convex, plane and concave mirrors and lenses,\textsuperscript{19} he did not mention projection of a real image onto a screen by lens or mirror. Nor did Roger Bacon (1214-1294), the leading optical experimenter of his day. Given the written record for other uses of mirrors, optical devices and drawing aids for artists—from the baccolo of Euclid to perspective machines—it is hard to understand why the putative mirror projection system would uniquely elude the 15th-century record. Can it really be true that artists somehow obtained the devices, figured out how to use them and, so far as we know, nobody—scientists, patrons, mirror-makers, artists or church officials—left a corroborating written record?

Of course it is still possible that van Eyck used his careful eye, talent and oil paint—much as N. Williams painted (the simpler) “Chandelier” (2003); see Fig. 9—and obtained good perspective. After all, a painting such as van Eyck’s may look realistic and seem “in perfect perspective” because it is rendered in crisp, sharp contours in oil paint, rather than strictly obeying the laws of geometrical perspective. Finally, I note that the burden of proof lies with Hockney and Falco: their task is not merely to show that their explanation is consistent with the optical evidence or even that it fits the evidence well, but instead to show that alternative, non-optical ones cannot fit the evidence.\textsuperscript{20}

In any case, it is clear that modern analysis techniques from optics and computer vision will continue to shed light on the secrets of the Old Masters.\textsuperscript{21, 22}

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References

1. David Hockney, Secret knowledge: Rediscovering the lost techniques of the old masters (Viking Studio, 2001).
15. Richard Hartley and Andrew Zisserman, Multiple view geometry in computer vision (Cambridge, 2002).
16. Giambattista della Porta, Magia naturalis, particularly Book XVI, chapter VI (1589).
18. Witelo, Perspectiva, particularly Librum VII, Proposition 60 (translated in 1535).