OPTICS AND REALISM IN RENAISSANCE ART

A much publicized assertion holds that 15th-century painters achieved a new level of realism with the help of lenses and mirrors. But recent findings cast doubt on that idea

By David G. Stork

PORTRAIT OF GIOVANNI ARNOLFINI AND HIS WIFE, JAN VAN EYCK, 1434 © THE NATIONAL GALLERY, LONDON (*this page*); FROM "REFLECTIONS OF REALITY IN JAN VAN EYCK AND ROBERT CAMPIN," BY A. CRIMINISI, M. KEMP AND S. B. KANG IN *PROC. MEASURING ART: A SCIENTIFIC REVOLUTION IN ART HISTORY*, PARIS, MAY–JUNE 2003, AND IN *HISTORICAL METHODS*, VOL. 36, NO. 3; SUMMER 2004 (*rectified reflection in van Eyck's painted mirror*); © THE NATIONAL GALLERY, LONDON (*infrared reflectogram of hand*); ELIZA JEWETT (*perspective lines*)

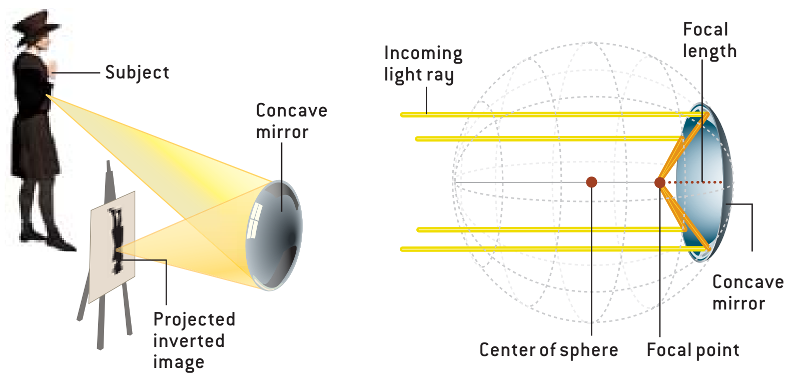
When we consider the grand trajectory of Western painting, we see something very interesting taking place at the dawn of the Renaissance. Before roughly 1425, most images were rather stylized, even schematic, but afterward we see paintings that have an almost photographic realism. For instance, *Portrait of Giovanni Arnolfini and His Wife*, by the early Renaissance master Jan van Eyck (1390?–1441), reveals a three-dimensionality, presence, individuality and psychological depth lacking in earlier works. For the first time, we find portraits that really look like us. What happened?

In seeking to explain the emergence of this remarkable new art, or *ars nova* as it was called, the celebrated contemporary artist David Hockney came up with a bold and controversial theory. He claimed that Renaissance paintings look realistic—possessing what he called "the optical look"—because artists used lenses and mirrors to project images onto canvases or similar surfaces and then trace and paint over the results. [*Editors' note: This theory is set forth most completely in Hockney's 2001 book* Secret Knowledge: Rediscovering the Lost Techniques of the Old Masters.]

It is well known that in the 18th and 19th centuries some painters made use of images optically projected onto their canvases. But Hockney's theory would push the earliest date a quarter of a millennium earlier still. And so important are these optical instruments and techniques to his theory that Hockney says the history of art from that time is intimately linked with the history of optics itself.

HOW MIRROR PROJECTION WORKS

A concave mirror will project an upside-down image of a subject onto a screen set at some distance from the mirror (*below left*). Concave mirrors can be considered sections of a sphere (*below right*). The focal length of a mirror cut from the sphere is half the radius of the sphere. The focal length is the distance from the mirror to the focal point—the point at which incoming parallel light rays reflected from the mirror meet. An equation relates the distances between the subject, the mirror and the projected image and thus makes it possible to establish after the fact such details as the location of the mirror and its focal length.



As part of an examination of this theory, other scholars and I have used optical and computer-vision techniques to evaluate two of van Eyck's paintings that Hockney and his collaborator Charles Falco, a physicist at the University of Arizona, adduce as evidence. In this article, I lay out the results of these findings, which are representative of a broad class of arguments about the theory.

Mirror Projection

ACCORDING TO HOCKNEY, some artists as early as 1425 employed a primitive camera obscura. A traditional lens-based camera obscura is a precursor of the modern photographic camera, but without film. It relies on a converging lens to project an inverted real image of a scene onto a viewing screen. (A projected image is called "real" because light actually strikes the screen, much as an image exposes film in a camera. The other, "virtual," type arises when light only seems to come from an image, your face in the bathroom mirror, for example.)

For a number of historical and technical reasons, Hockney envisions a camera obscura based not on a lens but on a concave mirror (curved inward like a shaving or makeup mirror), which can also project an image onto a screen. The artist would illuminate his subject with sunlight and point the mirror at the subject to project a real inverted image onto a canvas or an oak panel—called the support. The artist would then either trace the contours of the image and apply paint or perhaps even paint directly under the image, although, as Hockney acknowledges, painting under optical projections is extremely difficult.

Such a mirror-based camera obscura is simple by today's standards, but at the time of van Eyck it would have represented the most sophisticated optical system on the planet, requiring greater precision in the shape and arrangement of the mirror and more stringent requirements for illumination than any known system. No contemporary writing by scientists, artists, patrons, clergy or mirror makers that I have been able to uncover indicates that anyone had even seen an image of an illuminated object projected onto a screen by a mirror or lens. Given the surviving records for all manner of other optical systems and mechanical drawing aids, the absence of evidence for the Hockney projector is difficult to explain.

I examined three key technical properties of this proposed concave-mirror projector. First, focal length. A concave mirror reflects parallel light rays so that they meet at the so-called focal point. (If you try to use such a mirror to start a fire in sunlight, you place the tinder at the focal point.) The distance from the mirror to the focal point is its focal length. A mathematical formula—the mirror equation—defines how far apart the subject, mirror and support can be and still produce a sharp image on the support. These distances, in turn, govern the size of the projected image. For example, a photographer will choose a long-focal-length, or telephoto, lens to zoom in on a baseball pitcher to make his image large; he will use a short-focal-length wide-angle, or "fisheye," lens to zoom out, revealing the fans throughout the stadium. The second property concerns the brightness of a projected image, which depends on the focal length and facial, or surface, area of the imaging mirror. The third property is geometrical perspective: an image projected by a mirror obeys the laws of perspective, just as the projected image that exposes a photograph does.

Van Eyck's *Portrait of Giovanni Arnolfini and His Wife* (1434)—one of

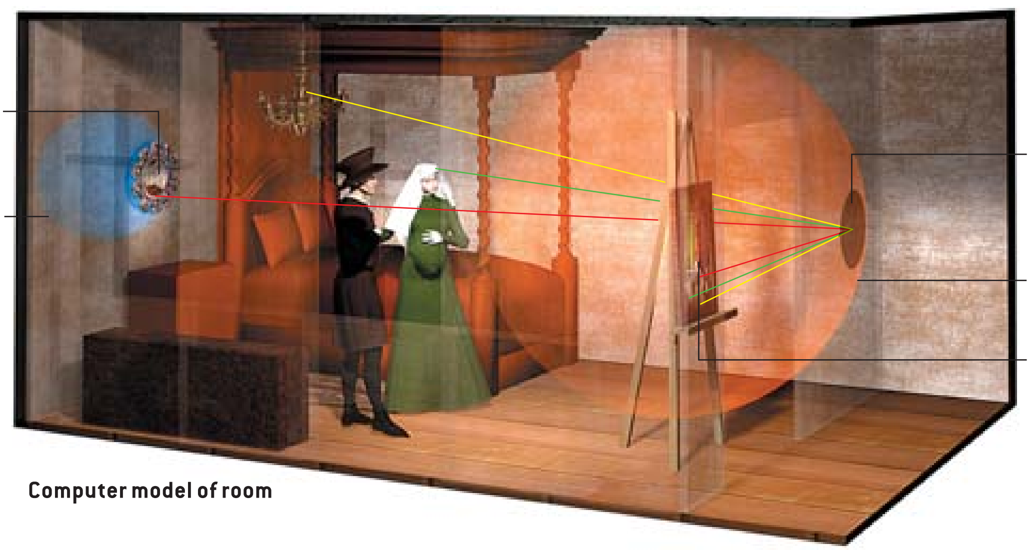
Overview/*Analyzing van Eyck*

- A theory put forward by artist David Hockney posits that as early as 1425 some painters secretly used optical devices—mirrors and lenses—in the creation of their works.
- Among the paintings used as evidence for the theory are two by Jan van Eyck from the first half of the 15th century.
- Scientific analysis of both paintings, including the use of computer-vision techniques and infrared reflectography, raises questions about the theory.

ELIZA JEWETT AND TOMMY MOORMAN

THE MIRROR IN ARNOLFINI'S ROOM

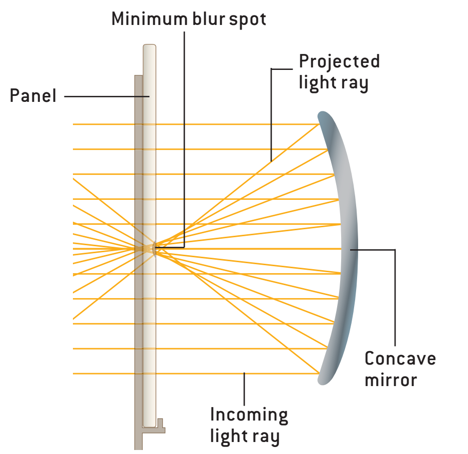
To test Hockney's proposal that the convex mirror in van Eyck's Arnolfini portrait could have been resilvered, turned around and used as a concave projection mirror, the author first made assumptions about the sizes of objects and their position in the room. He then used the rules of geometrical optics to establish the location of the projection mirror and the easel that would produce the sizes in the actual van Eyck painting [*see computer model below*]. Finally, he applied the mirror equation to find the focal length of the projection mirror. His results give a focal length of roughly 61 centimeters. If cut from a sphere, that sphere would have a diameter of 2.4 meters (*red sphere*). Analysis of the images in the mirror depicted on the back wall (*bottom left*) show that its focal length is approximately 18 centimeters, indicating that it might have been cut from a sphere 0.7 meter in diameter (*blue sphere*). Therefore, the convex mirror in the painting could not have served in reverse as the concave projection mirror. Other calculations and experiments show that the indirect illumination in Arnolfini's room was too dim to project a traceable image and, further, that any projected image would have been too blurry to yield fine detail (*bottom right*).



Computer model of room

To find the focal length of van Eyck's mirror, the author used a computer method developed by Antonio Criminisi of Microsoft Research in Cambridge, England, Martin Kemp of the University of Oxford and Sing-Bing Kang of Microsoft Research in Redmond, Wash. He was thereby able to adjust the radius of curvature, or bulginess, of the mirror to "unwarp" the painted image—that is, to make the beams, doorjambs and so on appear straight. The radius of curvature found in this way shows that the focal length of the mirror in the painting is roughly 18 centimeters.

Image in mirror with distortion corrected

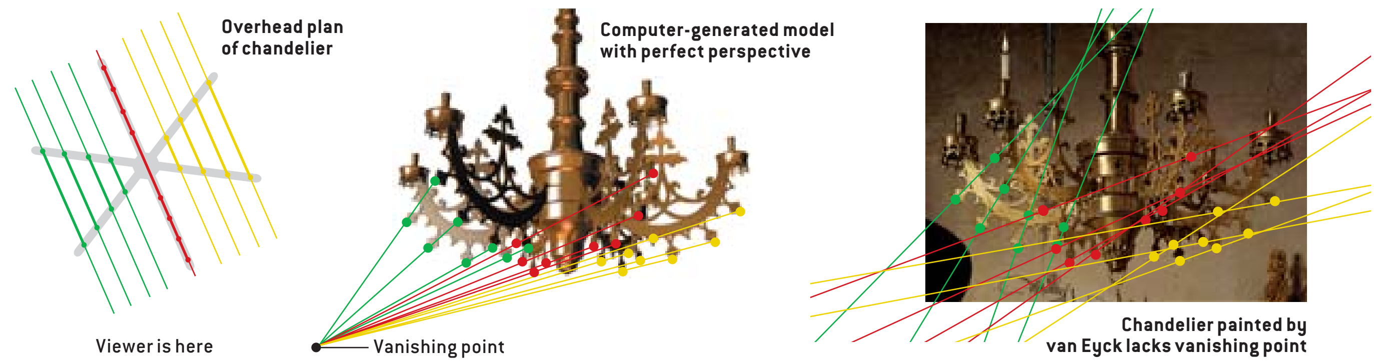


If the convex mirror in van Eyck's painting had been turned around for projection, its minimum blur spot—the smallest spot of light on the screen arising from a point on the subject—would have had a diameter of approximately one centimeter, much too large for projecting the fine details found in the painting.

JAMES SCHOENBERG AND DAVID G. STORK (*3-D rendering of Arnolfini room*); ANTONIO CRIMINISI ET AL. (*rectified reflection in van Eyck's painted mirror*); ELIZA JEWETT AND TOMMY MOORMAN (*drawing*)

THE CHANDELIER

The optical projection theory maintains that the ornate chandelier in the Arnolfini portrait is painted in perfect perspective, as it would be if it were based on a projected image. To address this claim, the author performed a perspective analysis on the chandelier. In the bird's-eye view, or plan, shown on the left, the six-armed chandelier is assumed to be hexagonally symmetric. Corresponding structures (*colored dots*) on any pair of arms define lines parallel to the floor and perpendicular to the vertical plane bisecting those lines; thus, all these lines, such as those shown, are mutually parallel in space. If the physical chandelier in the painting was symmetric—or close to it—and had been painted in perfect perspective, the parallel lines would meet at a vanishing point (*center*). Such lines similarly constructed for the Arnolfini painting (*right*) deviate wildly, however. Clearly, either the chandelier was not drawn under a projected image or it was not even close to being symmetric.



the earliest masterpieces in the northern Renaissance—is a key exhibit in Hockney's theory. Much can be said about the symbolism and meaning in this extraordinary painting, but I will concentrate on a few dozen square centimeters at its center. Whereas art historians will dilate on the symbolism of capturing the visual world in the convex mirror prominently displayed on the rear wall, I will be concerned instead with its optical properties, such as its focal length and light-gathering power. Whereas art historians will discuss how the splendid chandelier shows the wealth and stature of the Italian businessman Arnolfini, then visiting the Low Countries, I will show how such metalwork reveals much about geometrical perspective and projections.

Art historians rightly caution against taking the Arnolfini portrait or indeed any painting of that time too literally, but if we are to judge the projection theory, we must provisionally assume with Hockney that the painting is somehow based on a faithful copy of a projected image.

Let us look first at the convex mirror, perhaps the most famous mirror in all art. Today such mirrors are familiar at convenience stores or blind driveway entrances because they reveal a wide-angle view on the world. Unlike concave mirrors, the convex kind produces right-side-up virtual images, smaller than the original object, which cannot be projected onto a canvas. Hockney surmises, however, that this con*vex* mirror could be turned around and used as a con*cave* projection mirror: "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."

To test this conjecture, I computed the focal length of the mirror putatively used for projection and that of the concave mirror that would have been created by reversing the convex mirror. I then compared these focal lengths. I found that the projection mirror would have a focal length of 61 ± 8 centimeters, the uncertainty the result of my imperfect knowledge of the sizes and placements of objects in the room. The focal length of the concave mirror made by flipping the convex mirror is 18 ± 4 centimeters. The focal length of the depicted mirror (reversed) differs from that of the putative projection mirror by some 43 centimeters. The depicted mirror, turned around, could not have been used as a projection mirror for the full painting.

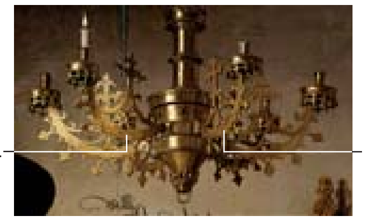
In fact, manufacturing a mirror from a blown-glass sphere that *could* have been used would have been beyond the capabilities of Renaissance technology. The diameter of a sphere is four times the focal length of a concave mirror cut from it. To get a projection focal length of 61 centimeters requires a glass sphere whose diameter is a whopping 2.4 meters. Moreover, a mirror that is a section of a perfect sphere will produce a blurry image of each point in Arnolfini's room; each point is spread into a "blur spot" on the support, which I calculated would be several times the size of the fine detail in the painting. Any of the inevitable manufacturing deviations

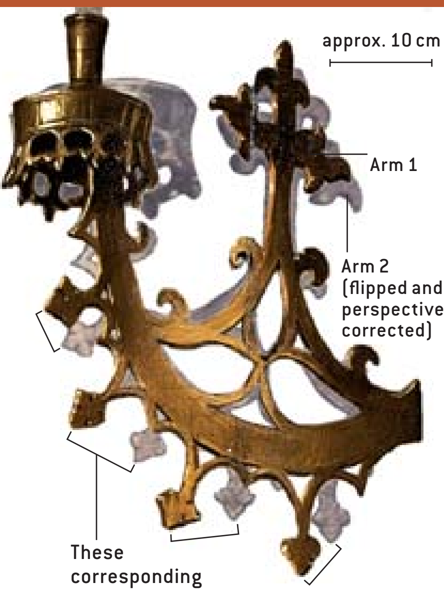
THE AUTHOR

DAVID G. STORK is chief scientist at Ricoh Innovations as well as a consulting professor of electrical engineering at Stanford University, where he has also taught in the department of art and art history. A graduate of the Massachusetts Institute of Technology (B.S.) and the University of Maryland (Ph.D.) in physics, Stork studied art history at Wellesley College and was Artist-in-Residence through the New York State Council of the Arts. He holds more than 15 patents and has published five books. His deepest interest is in adaptive pattern recognition by machines and humans.

FROM LEFT TO RIGHT: ELIZA JEWETT (*drawing, perspective lines*); JAMES SCHOENBERG AND DAVID G. STORK (*3-D rendering of chandelier*); JAN VAN EYCK, 1434 © THE NATIONAL GALLERY, LONDON (*chandelier detail from Arnolfini portrait*); ANTONIO CRIMINISI (*computer simulation of chandelier arms*)

To investigate the possibility that the actual chandelier was significantly asymmetric, the author and Antonio Criminisi used a computer simulation to depict the painted chandelier (*below*) and then flip the arms and lay them atop one another, as is shown at the right for two of the arms. The analysis revealed offsets of as much as 10 centimeters. This degree of sloppiness in the actual chandelier is unlikely, according to measurements made of other chandeliers from the period in museums and similar computer analysis of photographs of such chandeliers.





would degrade the image still more.

Renaissance craftsmen, moreover, would have faced severe technical challenges in silvering and sealing a concave mirror, which required the application of hot tar and pitch on the outside of the glass. To my knowledge, no such concave mirrors made by reversing a glass sphere survive in museum collections, and no contemporary documentary evidence indicates that anyone made concave mirrors by reversing blown glass spheres.

My finding about the unlikely focal length of the putative projection mirror has a second implication, even more constraining to the Hockney theory. If we can rule out fairly large blown-glass spherical mirrors, that would seem to leave only small polished metal mirrors, which were known in the 15th century and indeed earlier. Mirrors of this type have poor light-gathering power, however. I calculated and experimentally verified that such mirrors with the proper focal length require that the object be illuminated by direct sunlight to yield a visible image on the support. It is hard to reconcile this requirement with the manifestly indirect indoor illumination in the Arnolfini portrait and in many early Renaissance paintings adduced as evidence by Hockney.

A Different Perspective

OTHER EVIDENCE throws doubts on the suggestion that van Eyck painted the Arnolfini portrait under a projection onto the oak panel. A projected image obeys the laws of perspective, but the perspective lines of the floor, window casement and other features in the painting do not meet at a vanishing point as they should. The perspective is consistently inconsistent.

What is more, a technique called infrared reflectography reveals significant wet underdrawing (that is, preliminary drawing done with oil paint, not pencil) and several revisions throughout nearly all the painting, in particular for Arnolfini's hands, feet and head—hardly an indication of tracing a projected image.

The splendid chandelier, or *lichtkroon* (in Dutch, "light crown"), has no underdrawing. Perhaps this challenging section was drawn under projection, out of doors, the chandelier illuminated by direct sunlight. According to Hockney, the chandelier "is in perfect perspective," as it would be if drawn under projection. The image certainly appears to be in perspective. But is it?

As a start at addressing this question, I drew and extended lines linking corresponding structures on the arms of the painted chandelier [*see box on these two pages*]. The laws of geometric perspective guarantee that in a concave-mirror projection of a symmetric chandelier onto van Eyck's support all parallel lines would meet at a vanishing point, just as the image of train track rails meet on the horizon in a photograph. But the lines I drew for the painted chandelier are quite haphazard—like pickup sticks tossed carelessly onto a floor—and show no hint of a coherent vanishing point underneath the chandelier.

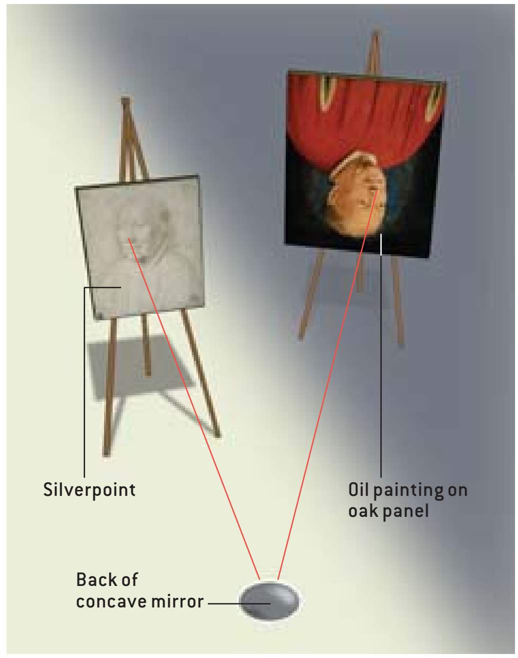
This result, taken alone, does not rule out the possibility that an *asymmetric* chandelier was the source of a projected image. But what are the chances that the actual chandelier that served as van Eyck's model was radically asymmetric?

To answer this question, Antonio Criminisi of Microsoft Research in Cambridge, England, and I used his new rigorous computer-vision algorithms to "undo" the perspective in each arm; we then placed the corrected images atop one another. Any difference between these perspective-corrected arms shows the "sloppiness" that would be necessary in the construction of the chandelier for it to be consistent with the projection theory. We found that whereas a few portions lined up fairly well, overall the variation among the arms was very large indeed—as much as 10 centimeters.

Most scholars believe that the arms of brass and copper alloy European metalwork were cast whole from a single mold in van Eyck's time; crockets were not soldered or riveted onto the main arms. As such, all the arms should have had much the same shape. Criminisi and I confirmed the high symmetry of such metalwork by applying our perspective analysis to a true projection—a modern photograph—of a direct casting of a 15th-century four-arm *lichtkroon*. The perspective-corrected arms match extremely well; the maximum discrepancy among arms is about a millimeter. Our perspective tests of several large, complex candelabras and chandeliers in the Royal Museums of Art and History in Brussels show all are significantly more symmetric than the Hockney projection theory

COPYING CARDINAL ALBERGATI

According to Hockney's theory, van Eyck copied and enlarged a silverpoint study of Cardinal Niccolò Albergati by means of an epidiascope, a primitive device that projects an image from one flat surface onto another. The silverpoint (*on left in diagram*) would sit on an easel, illuminated by bright light, presumably sunlight. The oak panel would rest on another easel in dark shade (*on right in diagram*), so that the dim, inverted image projected by the concave mirror would be visible. Van Eyck would then trace over the projected image in pencil, turn the panel right side up and commit paint to it.



When the Albergati oil portrait is reduced by roughly 40 percent and overlapped with the silverpoint study (*left*), the contours match to within a millimeter, showing the high fidelity of the copying scheme. The ear on the oil painting, however, shows a shift to the right and an extra 30 percent enlargement. Hockney suggests that van Eyck accidentally bumped the silverpoint, the oil painting or the mirror and then traced the shifted image. The author considers it unlikely that van Eyck would have failed to see such a large shift; he suggests that a drawing aid such as a compass or a *Reductionszirkel*—a crossed pair of rods pivoted at a point other than the center—could have been used to enlarge the drawing. (To use a *Reductionszirkel*, the artist places two tips of the instrument on the original, then turns the device upside down to mark a scaled distance on the copy.)

Richard Taylor of the University of Oregon used a *Reductionszirkel* to copy the Albergati silverpoint (*far left*). When his copy (*near left*) was digitally scanned and overlapped with the source image, the fidelity proved to be quite good, save for the region of the ear. The *Reductionszirkel* could offer an explanation for the shift and additional enlargement of the ear: van Eyck started copying the left side of the face, using the instrument to mark the separations between the mouth and the tip of the nose, between the two eyes, and so on. But the *Reductionszirkel* has a limited range, and van Eyck could not stretch it wide enough to mark the separation between the chin and the ear. Therefore, he picked it up and moved it by eye to the side of the head near the ear and began again—in the process, shifting the ear in relation to the part of the face already drawn.

demands of the Arnolfini chandelier.

Underlying the projection theory is the belief that van Eyck could not have easily achieved his level of perspective accuracy, such as it is, "by eye"—that is, without optical projections. But what level of perspective accuracy *can* be achieved by eye? At my request, British artist Nicholas Williams painted several complex chandeliers without using any photographs, optics or perspective constructions. Our analysis of his paintings shows that the perspective is excellent—better than that in the Arnolfini chandelier—thus demonstrating that a skillful artist does not need projections to achieve good perspective.

Cardinal Albergati

NEXT I ANALYZED van Eyck's *Portrait of Niccolò Albergati*. The artist first made a drawing of Cardinal Albergati, executed within a three-day period in 1431. Done in the silverpoint technique, in which a metal stylus applied to specially prepared paper produces a sharply defined image, the drawing is clearly a study made in preparation for a more formal work. The following year, the artist made a larger copy of the portrait in oil on wood panel, which involved copying and enlarging an image from one flat surface onto another flat surface.

TOP LEFT AND *MIDDLE*: STAATLICHE KUNSTSAMMLUNGEN DRESDEN, KUPFERSTICH-KABINETT; *TOP RIGHT* AND *MIDDLE*: *KARDINAL ALBERGATI*, JAN VAN EYCK, 1435, KUNSTHISTORISCHES MUSEUM, VIENNA; TOMMY MOORMAN (*graphics, top right*); *BOTTOM*: MICHELE TAYLOR (*left*); RICHARD TAYLOR (*right*)

Hockney's collaborator Falco has suggested that van Eyck used an optical projector to create the oil painting—a primitive epidiascope, or opaque projector, consisting of two easels, one bearing the silverpoint in bright illumination (presumably direct sunlight), the other the wood panel in shade, presumably indoors or under some form of tent. A concave mirror would project a real inverted image of the silverpoint onto the panel, which van Eyck would trace. Hockney and Falco base this contention on two salient features of the portraits: the high fidelity of the (scaled) shapes and a residual discrepancy in the placement of portions of the image, particularly the ear [*see illustration on opposite page*].

The ear is shifted 30 degrees to the right in the oil painting; it is also 30 percent larger (in addition to the roughly 40 percent overall enlargement of the oil painting). Hockney and Falco explain this shift as follows: van Eyck traced part of the image projected in an epidiascope, then accidentally bumped the silverpoint, the oil or the mirror, and finally traced the remaining, now shifted, image.

But their explanation has problems. If van Eyck bumped the setup halfway through his work, he surely would have seen the mismatch between the shifted projected image and his tracing lines already committed to the support. I copied a reproduction of the silverpoint using a homemade epidiascope based on a small circular concave mirror and direct solar illumination, and when I deliberately "bumped" my own epidiascope, I found such a mismatch to be very conspicuous. It is unlikely that van Eyck, working closely on an important commission, would not have noticed such an offset.

The silverpoint could have been copied using a much simpler drawing aid such as a compass or *Reductionszirkel*—a pair of crossed rods pivoted at a point other than the center. The artist places two tips on the original, then turns the instrument upside down to mark a scaled distance on the copy. I asked Richard Taylor of the University of Oregon to build a *Reductionszirkel* and to use it to copy and enlarge the Albergati silverpoint. His accuracy is excellent, to less than one millimeter throughout most of the image. Curiously, his rendition of the ear is a bit off, perhaps because he started at the lower left and the limited reach, or range, of the instrument led to the error.

What Was the Source?

SO IF, AS IT SEEMS, Jan van Eyck did not use optical devices during the execution of his works, we are left with the initial question: What led to the increase in realism in Renaissance painting around 1425, for which van Eyck is perhaps the best representative? A constellation of reasons—some technical, some cultural—are traditionally put forth. There may even be an optical reason.

The early Renaissance is precisely when oil paints came into use, and indeed van Eyck is often called the father of oil painting. In the flat tempera painting of medieval art, the gradation of values that produces a three-dimensional effect was almost impossible to achieve. Oils, however, allowed for continuous gradation, as well as for novel glazing and layering techniques and an expanded range of colors, including much more vivid saturated colors. But perhaps the most important property of oil paints is that they dry far more slowly than previous media, thus allowing the artist to rework and develop an image over months or years.

At about this same time, Italian artists invented linear perspective. Based on a horizon line, a vanishing point, and orthogonal lines, or "visual rays," that lead the viewer's eye to the vanishing point, this mathematical system created the illusion of space and distance on a flat surface and allowed artists to depict scenes in a more naturalistic fashion. Another technical innovation of the period is that artists were for the first time studying cadavers and developing an understanding of muscles and skeletal structure.

Many cultural forces set the stage for the new art, too. The Renaissance brought a rise in secularism and in classical ideals of focusing on humans in the here and now. The increase in patronage was also important: Renaissance painters had to render a specific individual and his possessions. If van Eyck's portrait of Arnolfini was not faithful or flattering, then this powerful patron would not endorse the artist.

Christopher W. Tyler of Smith-Kettlewell Eye Research Institute in San Francisco has suggested an "optical" reason for the rise in realism, one quite unrelated to Hockney's: the growing prevalence of spectacles. It may be that artists who needed—and got—spectacles simply could see more clearly, especially in their close-up work on paintings. In fact, van Eyck's *Madonna with Canon van der Paele* (1436) shows the donor holding spectacles, and I infer from the bright spot cast by a spectacle lens that the lenses are converging, as would aid a hyperopic (farsighted) person for close reading—or a hyperopic artist painting fine details. Hockney has said informally that it seems as if Western painting put on its glasses for the first time around the dawn of the Renaissance. Perhaps he is more correct than he realizes. SA

MORE TO EXPLORE

Secret Knowledge: Rediscovering the Lost Techniques of the Old Masters. David Hockney. Viking Studio, 2001.

Optics at the Dawn of the Renaissance. David Hockney and Charles M. Falco. Proceedings of the Annual Meeting, Optical Society of America, Tucson, Ariz., 2003.

Did the Great Masters Use Optical Projections while Painting? Perspective Comparison of Paintings and Photographs of Renaissance Chandeliers. Antonio Criminisi and David G. Stork. International Conference on Pattern Recognition, Cambridge, England, August 23–26, 2004. Available at the author's Web site.

Reflections of Reality in Jan van Eyck and Robert Campin. Antonio Criminisi, Martin Kemp and Sing-Bing Kang in *Historical Methods* (in press).

David G. Stork's Web site is at **www-psych.stanford.edu/~stork/FAQs.html**

An exploration of David Hockney's theories is at **webexhibits.org/hockneyoptics/**