THEORETICAL PERSPECTIVE

Art History and the Criticism of Computer-Generated Images

James Elkins

ABSTRACT

As the field of computer graphics expands, it tends to be taught in a manner that is increasingly isolated from the history of art. The author shows how computer graphics can reconnect to wider sources of meaning in three arenas: (1) continuous traditions spanning Western painting and contemporary rendering techniques, (2) linear perspective, and (3) drawing. The comparisons are used to demonstrate that the history of art is intimately associated with the exploration of computer-assisted imagery, even though it remains largely absent from its pedagogy.

In science, engineering and architecture it is often said that computer graphics is an aid to visualization: it helps us understand complicated shapes such as enzymes, the trajectories of spacecraft, architecture and paintings. Behind this explanation is the notion that "spatial thinking," "visualization" and related capacities are more or less given—"hard wired" is the computer term—independently of history or of the technology in question. Computer graphics only verifies that assumption when it produces calculated facsimiles of the world. There is truth to this, but I would like to argue that we obtain it by ignoring the richer meanings that our computer-generated pictures might have.

There are two intertwined components to this notion: one has to do with history, the other with technology. Computer graphics is inextricably linked to the history of Western picture-making. The expressive meanings, artistic strategies and conventions of that genre continue to underwrite developments in computer graphics, especially when they are not acknowledged. The result, I will suggest, is that we have come to respond to our creations in an especially narrow way, excluding historical and expressive meanings or rewriting them as matters of physics, neurophysiology or personal, ahistorical "artistic judgment."

This would then be a reason to say that our discourse about pictures has changed since the advent of computers. I would add that the gradual specialization of thinking about pictures is a larger phenomenon bound up with modernism itself. But it is also possible to argue—and this is the second, technical aspect of my claim—that our ways of thinking about space have also been changing. We have been moving away from complexity and toward an ideal of rapid communication and schematic clarity. Our pictures are simpler, both in the fine arts and in scientific illustration. There is a practical reason for this, since it is no longer necessary to create complicated networks of lines in order to place three-dimensional (3D) objects on flat surfaces (computers and photographs do that invisibly). But I do not want to imagine practice as the enigmatic cause of the history of seeing. Artists and illustrators have been interested in avoiding intricate constructions in part because the way we imagine space itself has changed. The lumpy, crowded spaces of Western painting have been replaced by the sheer, limitless spaces of contemporary graphics.

In each of these themes it is tempting to see a gradual im-

James Elkins (educator), Department of Art History, Theory and Criticism, School of the Art Institute of Chicago, 37 S. Wabash, Chicago, IL 60603, U.S.A.

Received 9 February 1993.

An abbreviated version of this paper was delivered at the joint meeting of the American Historical Association and the History of Science Society in Washington, D.C., chaired by Barbara Stafford, in December 1992.

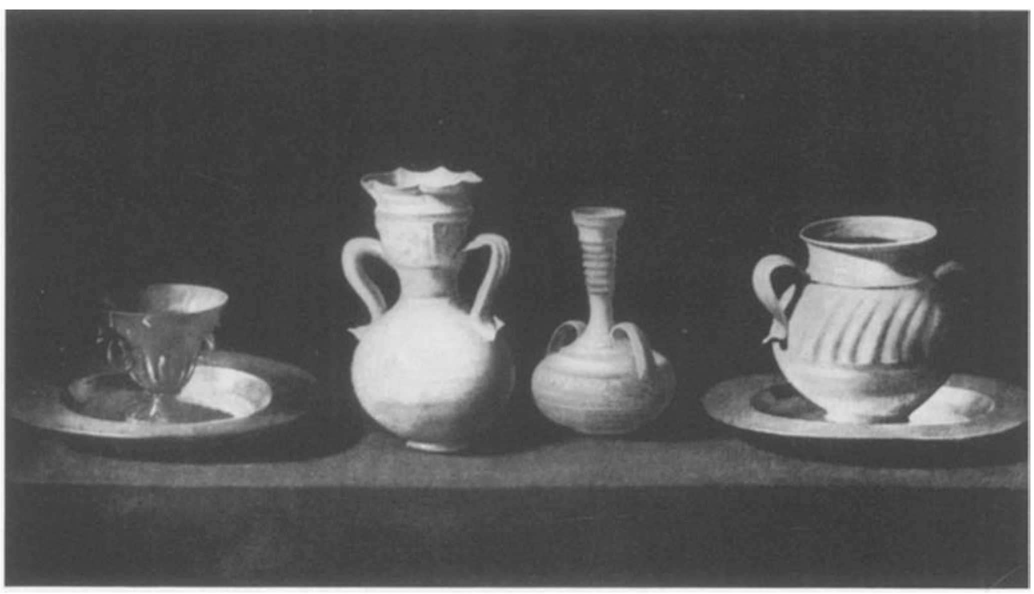
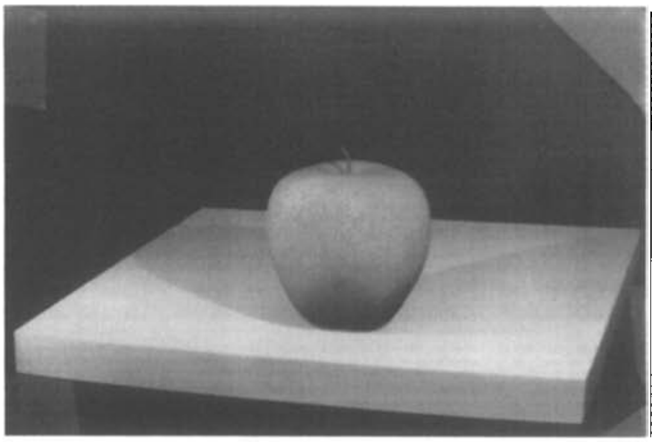
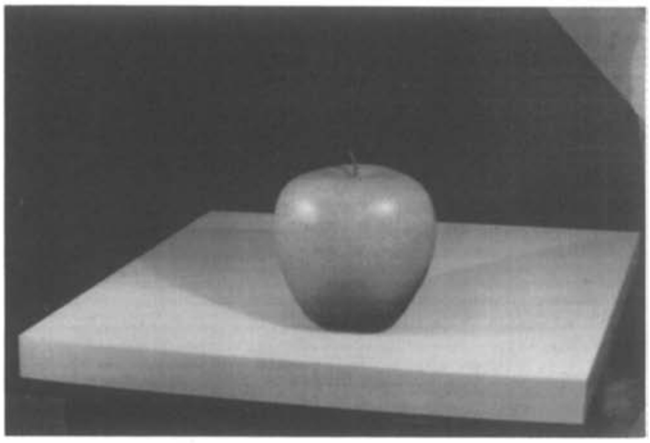


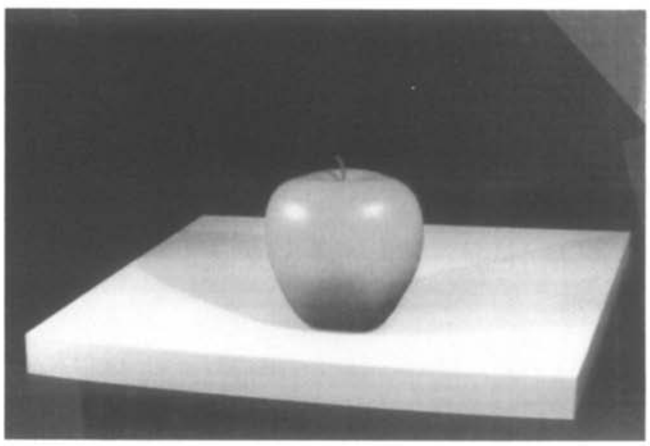
Fig. 1. Francisco de Zurbarán, *Bodegón Cambó*, oil on canvas, 0.5 × 0.8 m, 1633–1640 [24]. (Madrid, Museo del Prado) Like other simple, geometric still lifes, Zurbarán's are plausible historical antecedents for contemporary practices in computer graphics. From Martin Sebastian Soria, *The Paintings of Zurbarán* (London: Phaidon, 1953), Plate 13.



(a)



(b)



(c)

Fig. 2. Woodrow Barfield, *Demonstration of Lambert, Phong, and Blinn Rendering.* (Courtesy Woodrow Barfield) Color maps with variations on two light sources and two shadows produce (a) Lambert, (b) Phong and (c) Blinn renderings. The lighting subroutines in contemporary graphics proceed in accord with mathematical models and empirical observation rather than with historical inquiry.

poverishment of the concept of what a picture is. But having said that, I want to be careful not to sound as though I am valuing older pictures over newer ones. The spatial thinking that goes into computer-assisted drawing is more rapid and less pictorially informed than in previous centuries, but it is also lucid and schematic as never before. The questions that arise from these differences have to be debated seriously without falling prey to the humanist temptation to decry "illiteracy." Computers *are* illiteracy, and that has exhilarating effects for the question of what pictures can be.

It may not be necessary to defend my penchant for taking computer graphics seriously and talking about it within the wider histories of art; but it is symptomatic of the growing disconnection between art history and computers that I would ordinarily have to preface an essay or lecture with some such disclaimer. In particular, art historians are wary of the "high-tech" look of computer-generated images, and they tend to keep away from them for that reason alone. In a sense, this is a self-fulfilling prophecy: as long as the majority of art historians shy away from computer art, the historical discourse surrounding the new images will remain an impoverished "ghetto" [1]. Here is the way my prefatory apologia might sound, if I were presenting this material to art historians:

It is true, I would point out, that any new technology seems at first to have an overwhelming, often irrelevant meaning that comes from the peculiarities of its medium. When prints first appeared in the fifteenth century, they had such a different "look" that they were segregated from more traditional media. The "look" soaks up the nuances that may also be developing in the nascent medium. Computer graphics look steely, technological and often nerdy and escapist. One rarely sees a computer-generated image that does not seem to belong to some fantasy of childhood or adolescence. Often the medium does not seem to have been capable of breaking through those associations and beginning to explore more nuanced meanings. But this is something that happens to each new technology in turn, and if we look away on account of the unpleasant glare of technological references, we risk missing the development of new meanings—and most importantly, we tend to assume that the technology is contributing something superficial—such as efficiency—when it may also be bending artistic purposes in new directions.

This kind of introduction, which is routinely necessary to engage art historians with questions of computer-generated images, is a sign of the growing separation between the pedagogy of technological and traditional media.

Visualization and Historical Precedent

"Visualization" has a long history, beginning with the Platonic Idea and continuing on through nineteenth-century interest in "visible" geometry [2]. (Here's an example of a typical nineteenth-century visualization problem, which recently surfaced at a scientific conference: according to one report, "even professional mathematicians" have a hard time "seeing" that a tetrahedron—a perfect pyramid made of equilateral triangles—can be cut into exactly equal halves by a plane that intersects it in, "of all things," a precise square [3].) The field currently known as "visualization" is mostly concerned with computer graphics and asks how mathematical and physical concepts can be rendered realistically [4]. Researchers in this field want to know how lights reflect off various surfaces, how shadows are produced and, in general, how an abstract "object," which typically exists only as equations or raw data, can be made to appear solid.

In the great majority of cases, that solidity or realism takes its cues from a remarkably specific model: a tabletop, set against a matte grey backdrop, theatrically lit with a strong diffuse main "spot" and a weaker "fill," sometimes with the addition of a specular highlight. It may be because I am an art historian that this nearly universal setup does not seem to me to be merely a matter of the kind of programming that is easiest to manage, of the a priori facts of vision or of the empirical study of lights and shadows. It reminds me rather insistently of a specific genre of Western painting—the still life (Fig. 1). Like Western still lifes from the late Renaissance onward, these computer-graphics images rely on a short list of sturdy conventions: (1) a diad or triad of light sources arranged, in accordance with an academic regimen first developed in the fifteenth century, to produce lights, shades, highlights and reflected lights (*lumen, umbra,* and *splendor,* in the original terms); (2) a contrast between diffuse light and specular highlights (first codified by Leonardo da Vinci); (3) a theatrical setting with darkened backdrop; and (4) organic forms playing against geometric surfaces. People who work in visualization speak about these same terms, using their modern near-equivalents. But the question is always why the illusion works. Why do we perceive "Phong" rendering of light as more realistic than "Blinn" or "Lambert" (Fig. 2)? The answer may not be purely neurological or neurophysiological; it may also be historical.

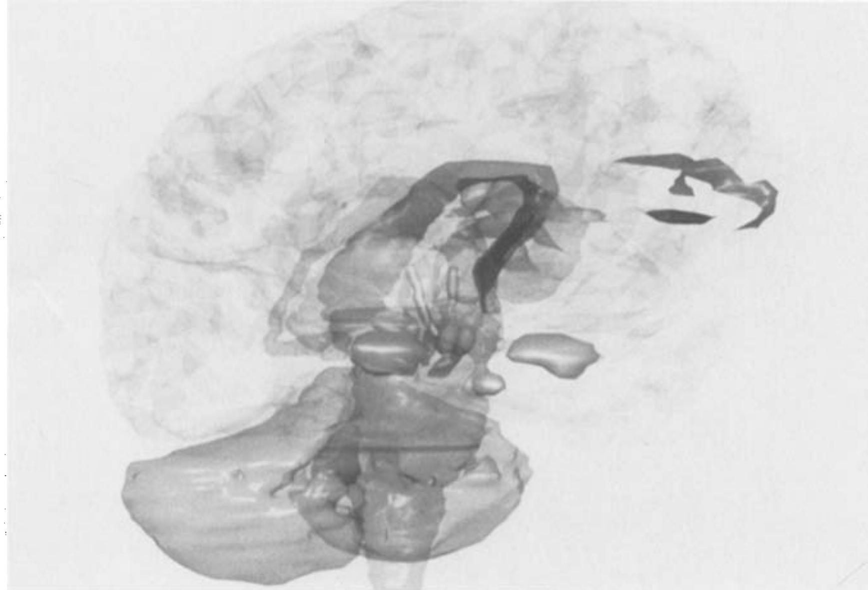
I should say in passing that still life is not the only genre of painting that informs computer graphics. There are recurrent disputes at the National Aeronautics and Space Administration (NASA) because of planetary scientists' habitual use of color enhancement and vertical exaggeration of planetary topography [5]. It might be argued in this connection that they want to remake the strange, hard-to-see images from space into familiar landscapes. Images from space are normally "enhanced" or "processed" in one way or another. The crippled Hubble space telescope's pictures are sharpened by "image deconvolution," and often the routines involved in such procedures and their resulting textures have more than a passing resemblance to the conventions of abstract painting. In a similar way, architectural drawing finds its way into the repertoire of computer visualization. Amazing depictions being made of the structure of the universe (with its "Great Wall," "filaments" and "bubbles") represent the largest forms ever put into pictures (excluding, I suppose, some pictures of God), and they are made possible by a massive accumulation of data points (here, galaxies) coupled with the simplest pictorial conventions (sections, parallel projections)—borrowed, ultimately, from architecture [6]. Even the special qualities of the video screen owe their appearance largely to the past. Large rectangular pixels, a trademark of computer illustration, are arranged and printed in ways that are derived from the history of painting—especially from cubism.

These topics call for extended investigations, and they are more specific than the wider points I want to make here. Despite these and other connections, I would say that still life remains the principal model for most of what happens in computer graphics. This can only seem insignificant if we say that both Western still life and modern computer graphics are responding to facts of vision and a common mode of interacting with objects. Without denying that component, let me rearrange the question and ask what meanings are produced when computer graphics takes Western still life as its model.

To begin with, there are questions of propriety. Why is a tabletop, with two diffuse or specular light sources and a neutral matte background, the appropriate arena for imagining such diverse objects as proteins, Buckyballs (new carbon compounds), broken bones, tumors, molecular landscapes, dolphin skulls and robotic animations? (I am naming some of the objects "visualized" that way at the 1992 SIGGRAPH computer conference.) Baroque artists thought of peaches, bread, flowers, tubs of butter, knives and flies as still life objects, but they put people and landscapes in other kinds of pictures. We use the conventions of still life far more widely, leading to moments that seem pictorially inappropriate by historical standards.

Beyond these questions, there are matters of motivation. Why would we want a molecule to look like a balloon animal? Why would we want the inside of the brain to look like cellophane (Fig. 3) [7]? Why is it best to think of atomic-scale phenomena such as the "Fermi surfaces" of superconducting "Buckminsterfullerenes"—which have no appearance whatsoever, since they are comprised of parts that are shorter than the wave-

Fig. 3. Phil Mercurio, *Human Brain,* 1992. SIGGRAPH '92 stereo slide set (No. 37/38) [25]. (Visualization: Phil Mercurio, Neurosciences Institute; data: Robert B. Livingston, University of California, San Diego.) Translucent sheets not only serve scientific ends, but also partake in an aesthetic of painless transparence shared by Baroque artists (see Fig. 4).



lengths of visible light—as yellow and purple rubber sheets (Color Plate A No. 2) [8]? Are these images that simply make visible something that was invisible? Or are we responding to a desire to see forms that are clear, solid and suitably "enhanced"? What about things that are patched, soiled, ambiguous, dusky and dirty—that is, what about the great majority of pictured forms from the past? In computer graphics, the rendering of mottled textures is a special problem called the "dirty old couch problem." But it may be that there is more here than meets the eye. We may be solving problems not only because it is simpler to do so, but because we want to. These are matters of motivation—of expressive meaning—as soon as we stop taking either computing ease or the neurophysiology of vision as necessary and sufficient explanations of software routines.

Motivation and meaning are easier to address in the case of the human body. The body is never simply "imaged" and no electronic cut is entirely painless. If a body is represented with hard, rubberoid surfaces, and a living subject with leather or plastic-wrap membranes, those choices are as deeply expressive as, say, Pinturicchio's wooden mannequins or Ingres's soft, waxen fingers. There are many parallels to be explored here. There is an entire history of bodies that are deliquesced into shimmering veils, encompassing both Tiepolo's watery washes (Fig. 4) and the iridescent mylar of Phil Mercurio's cerebral tissues (see Fig. 3). Or we might compare the dense, almost sticky surfaces of a vertical section through a mummy's head (Fig. 5) [9] to Rembrandt's tacky pigments (Fig. 6). Choices of textures, reflected lights and colors (or, to put these into computer language: "texture mapping," rendering routines, reflection models, radiosity and color palettes) for bodily tissues each have psychological meaning. Some transparent renderings transparently repress the body's horrific nature, and some garish hues exaggerate the body's meaty colors. Many computer "sections" of living patients seem to deny the ancient opposition of inside and outside and the barrier of pain between the two [10].

Computer graphics is deeply connected to the history of Western painting and, by restricting analysis to technical points, researchers often fail to see how expressive meaning and the communication of data go hand in hand. There is discussion of "artistic qualities," the "impression" of a picture and especially its "aesthetics," but I would suggest that these terms are inappropriate substitutes for meanings that have developed historically.

Fig. 4. Tiepolo, *The Course of the Sun's Chariot through the Skies Inhabited by the Olympian Gods and Surrounded by the Creatures of the Earth and the Animals Symbolizing the Continents*, detail of a figure presumed to be the goddess Thetis, fresco, 22 × 5.4 m, 1740 [26]. Tiepolo and other Baroque painters explored the same aesthetic of transparence that serves contemporary imaging (see Fig. 3). From Antonio Morossi, *A Complete Catalogue of the Paintings of G.B. Tiepolo* (London: Phaidon, 1964) Fig. 264.

Even images that seem largely determined by mathematics have their share of history. In fractal geometry, mathematics determines only the forms and contours of images. Their colors are up to the individual programmer, and the fact that they are universally high-chroma, or "metallic," cannot be explained only by reference to the configuration of computer "palettes" or to the requirements of efficient communication of information. The color choices come from two sources: the bright, hallucinatory "Day-Glo" colors of the 1960s and 1970s, and the equally garish colors of fin-de-siècle decadent advertising art and kitsch, which is still visible on the covers of pulp paperbacks. (I am thinking of the science fiction covers showing exaggerated images of young women—"space babes"—wrapped in rags and lit by yellow, green and blue moons.) Conversely, artists who work with commercial paint software often disdain these colors without investigating what it means to work from some rejected aesthetic and toward another—particularly when that other is, itself, derived from certain traditions of painting. Nineteenth-century artists had an analogous problem when they tried to transmute the first commercially available pigments into the colors they imagined. There is an interesting contrast, in other words, between the dry, scientific literature on fractals and the particular artistic sources it utilizes. The meanings of kitsch, fantasy art and pop art are bundled into terms such as "aesthetics" and addressed as matters of personal "artistic" choice outside of history [11]. In that way, historically specific but unanalyzed preferences in pictures (for the commercial colors of pop art or the scenes of fantasy and escape codified in late romanticism) come to be seen as natural or universal and therefore expressively unproblematic.

Before we leave this topic, I might add that there are historical parallels with another great technological revolution, the invention of the camera. Like the camera, the computer has been adumbrated in previous technology: in the case of the camera, the camera obscura, camera lucida and microscope were essential progenitors; in the case of the computer, I would suggest that the relevant precursors were the conventions of technical, engineering and perspective drawing. Both inventions were entwined with contemporaneous experiments in the visual arts: in the case of photography, there was the

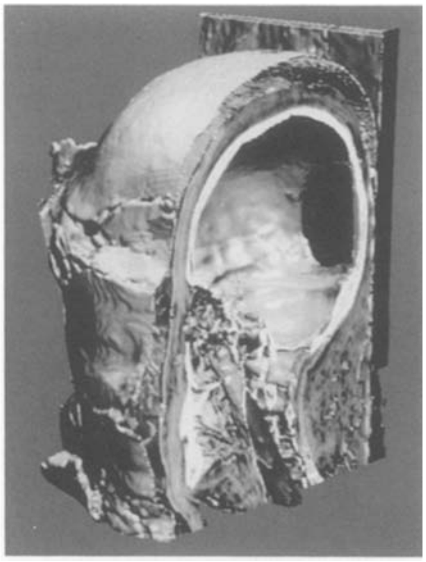


Fig. 5. Karl Heinz Höhne, *Cross Section of a Mummy's Head*, 1992. SIGGRAPH '92 stereo slide set (No. 23/24) [27]. (Courtesy Karl Höhne, Institut für Mathematatik und Datenverarbeitung, Universitäts-Krakenhaus Eppendorf, Hamburg.) A number of recent medical images move away from the "painless" sectioned body and begin to represent solid tissues and specific textures.

English watercolor tradition, Italian view painters and the entire aesthetic of the picturesque, which had such strong influence on what a photograph should look like [12]; in the case of computers, there was fantasy art, modernist architectural rendering, and movements such as minimalism.

COMPUTERS AND CONCEPTS OF SPACE

These historical connections might be understood as evidence that our concepts of space have remained reasonably constant, even while our ways of interpreting pictures have changed. But I do not think that is entirely the case. I also want to explore some ways that both pictures and the space they posit have altered along with the development of computers.

The twentieth century has seen an exponential rise in the literature on space, so much so that it would require a compact monograph just to define the kinds of space that have proliferated in psychology, philosophy, physiology, art history and art practice. There is objective space and subjective space, ideal space, imaginary space, surveyor's space, kinetic space, psychological space and psychophysiological space. There are metaphorical spaces, such as legal space, institutional space and social space. Each of these has been investigated using tools and terms borrowed, ultimately, from Euclid. In mathematics there are Euclidean spaces, projective spaces, four- and n-dimensional spaces, and spaces with fractional dimension (two-and-a-half dimensional space, for example). Currently, topology is the site of most explorations into new spaces. To name a few from a recent issue of *Mathematical Abstracts* there are nearness spaces, arcwise-connected metric spaces, G-spaces, semistratifiable spaces, nonseparable spaces and dispersed spaces. But most of these are not visualizable spaces; they are not available for spatial thinking. With some unimportant exceptions, they are not drawn at all [13]. Instead, they are sets of properties that have borrowed the word "space." To all of these we would have to add the practical infinity of spaces found in artworks, from the flattened spaces of Swedish boundary stones to the still inadequately described "facets" of cubism.

Out of this smorgasbord, computer graphics has chosen to represent only two kinds of space: those determined by perspective and by parallel projection. Of the two pictorial strategies, perspec-

Fig. 6. Rembrandt, *Portrait of a Fair-Headed Man*, detail, oil on canvas, 108 × 93 cm, 1667 [28]. (Melbourne, National Gallery of Victoria) Rembrandt's visceral, "waxy" textures evoke the possibility of sensation and pain in ways analogous to some texture-mapped surfaces (compare with Fig. 5). From Thomas Bodkin, *Rembrandt Paintings* (London: Collins, 1948) Plate 81.

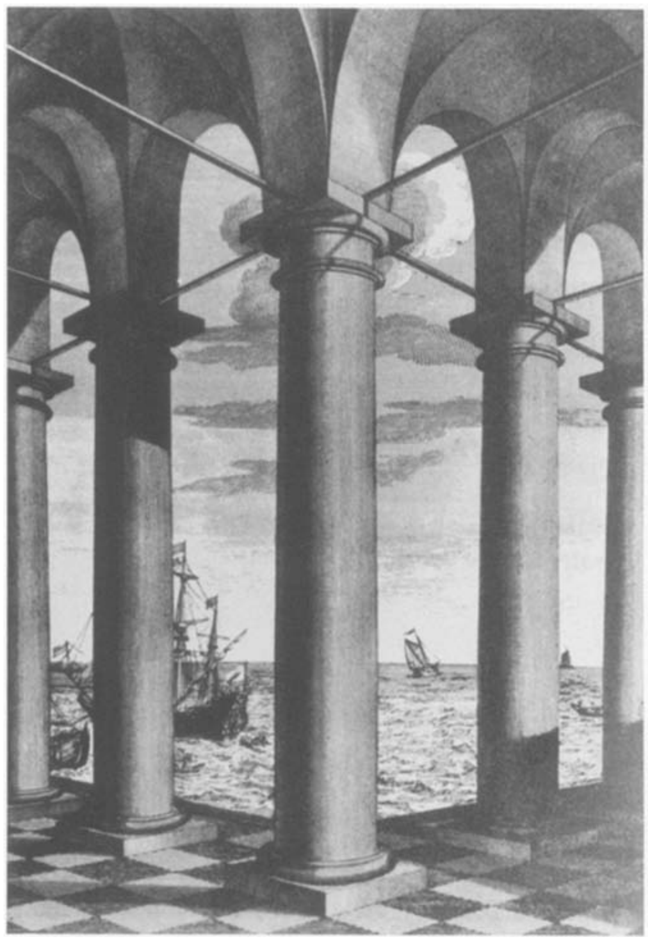


Fig. 7. Leon Battista Alberti, camerated (transverse) vaults and metal tie-beams, engraving, 8 × 10 in, 1726 [29]. The limitless perspective grid is only indirectly a heritage of Renaissance perspective. Sixteenth-century perspectivists tended not to emphasize the sense of infinity so central to contemporary virtual reality and other computer imaging.

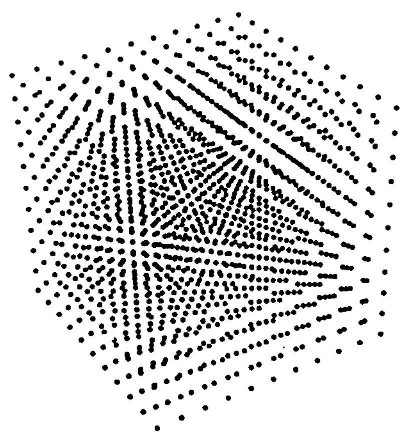


Fig. 8. A. J. Hanson, *Perspective of the Cubic Integer Lattice* [30]. The notion that space is infinite, isotropic and homogenous is a modern emphasis and is only intermittently connected to the earlier history of Western perspective images.

tive remains preeminent [14]. Renaissance perspective entails a sense of homogeneous space identical to the sense evoked by modern techniques and projection routines in computer software. But there is a quality of the Renaissance checkerboard pavement that speaks against our imagining it as a map of nearly infinite Euclidean space, as is implied in our plans and elevations [15]. In practice, Alberti's construction did not produce grid lines very far into the distance (Fig. 7) (in this example, there are two oblique ground lines rather than Alberti's single horizontal ground line). Alberti did not give instructions for extending the pavement, although we may certainly assume he knew how it could be done. It is difficult to continue transversals into deep distance using Alberti's method. The Albertian pavement, in effect, appears to be a kind of combined foreground and middleground, without anything beyond it. In addition, Alberti's construction does not include a horizon line, and horizon lines appear only intermittently in contemporaneous accounts. This tallies well with Renaissance paintings, since they normally show us objects and people only at a reasonable distance, after which either the squares give way to featureless pavement or open ground, or something else intervenes.

Even more interesting is the distinction within the pavement itself between foreground and middle ground. Alberti's checkerboard has a foreground because of the simple necessity of starting somewhere (with a "ground line") and constructing the checkerboard on top of it. The distinction between foreground and middleground occurs in paintings when painters who should have "known better" exaggerate the first few rows of transversals and draw the others to scale. Other paintings preserve the correct diminution but distinguish between foreground and middleground by a step or a change in pattern. In still other instances, the pavement is a foreground object and begins with an incomplete row of squares, as if to invite the viewer to imagine himself or herself standing on the same pavement. In short: Renaissance artists conceived of the receding checkerboard as a divided object, with a variety of fore-, middle-, and backgrounds.

In computer graphics, on the other hand, the checkerboard pavement is usually potentially infinite, enveloping the viewer and extending far into the distance. Even when it is cut in front and in back, as is necessary in order to show medium-size objects, there is often no sense of a boundary between the three regions; instead there are arbitrary, unmarked limits [16]. (The pavement might disappear at a preset distance, when it falls outside the "clipping window.") Contemporary computer artists and scientists make a point of emphasizing the infinite, homogeneous and isotropic qualities of rational space that have been around since the beginning. Space itself appears in our pictures as an infinite volume, always potentially empty (Fig. 8) [17]. Is it unfair to point out that the few "photorealist" computer spaces that have a foreground, middle ground and background are reconstructions of existing paintings, and that more purely fictive scenes are typically unbalanced, unlimited, or oblique views [18]? Computer graphics sometimes responds to a fuller repertoire of picture-making conventions, but that was a possibility that was also tempting for the first decades of photography [19].

Virtual reality may eventually change this predilection. The 3D visor, "magic glove" and "force-feedback puck" that scientists use to simulate environments bring back some of the Renaissance ideas that things have solidity and weight and that space can be crowded and hard to move through, for instance in simulated kitchens or battle environments. But at the moment, those technologies are also being used to fuel fantasies that I would link with a sense of unimpeded space. Molecular scientists use force-feedback pucks to get a feel for how one molecule might "dock" with another (Fig. 9): a scientist puts on the 3D visor and steps up to a machine hanging from the ceiling. He thinks he sees a molecule and tries to edge closer to it and "dock"—that is, chemically bond. The atomic forces sometimes repel him and sometimes draw him in. (And I might note in passing that this particular example also follows the still-life format.) Eventually, these machines might be used to guide microscopic robots ("telenanorobots") through other machines [20]. Though these possibilities each have scientific meaning, they also introduce perspective as an unlimited escapist fantasy: a characteristically modern meaning.

For the most part, our "space" is genuinely infinite, isotropic, homogeneous and purely Euclidean. It is not accidental that in the history of science those qualities were first used to define "space" in the late nineteenth century, when the kinds of realism and empiricism that inform contemporary scientific visualization were being developed. Before that, there was no call to define space so strictly, or to insist on its boundless self-similarity.

NEW MEDIA: NEW ART?

Having sketched these two points regarding the historical components of computer graphics, I want to close with a quick look at another major arena in the development of computer-assisted spatial thinking: the work that is being done by creative artists. At the beginning of this article I asserted that computer graphics programs are often assumed to be simple aids in the visualization of space. Those who teach creative art on the computer, on the other hand, also say that the computer is "coming into its own," developing into a new medium with its own rules that will be comparable in importance, independence and expressive depth to the strategies and possibilities of, say, painting, marble sculpture, film, printmaking or any of the other media that are taught independently of one another [21]. These two concepts of the nature of computers generally exist side by side and are frequently in direct competition with one another. This contradiction is a fundamental determinant of the teaching and development of computer graphics. Even as programmers, engineers, scientists and architects use computers to automatically visualize difficult objects, artists treat them as if they were in the process of developing the computer's intrinsic or essential nature, potential and properties. Departments of computer graphics in art schools and creative computer-graphics instruction in general are frequently underwritten by some version of this claim. But, in my experience, it is still far from clear what these intrinsic properties might be. Most of the things that happen differently on computers are simply a matter of increased efficiency and ease. Lines are effortlessly straight and even, there are no ink spills, massive calculations can be done instantly, and it is possible to produce stepless gradations of hue and chroma. Entire pictures can be rapidly redrawn to new line widths, "paint styles" and color specifications.

But these are things that could have been done before computers, though they would have taken longer. Exactly what do computers contribute? The artist David Hockney once experimented with a computer "paint program," but had only one observation when he was finished: he remarked that it was possible to cover a blue field with a red stroke on a computer and entirely efface the blue. This is related to the "undo" function that most graphics software has (sometimes software allows for multiple "undos," so that the artist can retract four or more successive marks). It can seem that the undo function and the stainless overpainting Hockney described are techniques new to art. But it seems to me that we are still talking about speed and perfection, rather than something entirely new. The same retractions and opacities are possible in oil or tempera if the artist has a little more patience. Knowing there is an undo function lets an artist work faster, more freely and more carelessly; but in comparison to, say, German Expressionism or sumi painting, how are we to say what effects the undo function has? Can we tell a picture done by a expressionist painter from a computer-assisted image whose spontaneity derives from the liberal use of the undo function?

It has been suggested that computer graphics is different because an artist can "save" a picture at a certain stage and then, after making a series of changes, return to the intermediate stage and begin again in a different direction. The versions of a picture can become ramified, like a family tree. This, together with the ease of "cutting and pasting," prompts artists to make pictures that are composites of many different versions of themselves. Here I would make two observations: first, it seems that this has been a practical possibility since photography, though not as easy; and second, there is still the problem of saying how pictures made in this fashion differ from those made in a more ordinary, linear way.

Let me close with a single example that seems to me both intriguing and characteristic. Computer graphics drawing pads are the only example I know of in the entire history of art in which the hand moves in one place and the drawing appears in another (i.e. on the screen) [22]. Students who learn to draw in this way, however, speak about "mastering" the technique: they work around it rather than probing it to find what it might be able to give them that centuries of normal hand-eye coordination could not.

It is not easy, I think, to point to something in studio practice that is different from painting in kind rather than in degree. This is an important complement to my general thesis that the earlier history of painting is continuous with computer-assisted drawing and painting. The example of drawing instruction helps us remember that a technological innovation does not usually or automatically give us another way of producing pictures—instead, it relies on strategies of picture-making that are in the air, from over-painting to the conventions of still life [23]. It also reminds us that even though a new technology may introduce genuine changes in the way we think about pictures, in the great majority of cases it will give us something old in the guise of something new. In all these cases, the history of art is a fitting context and carrier of meaning for explorations that are often seen as ahistorical or dependent on personal "skill" or "aesthetic."

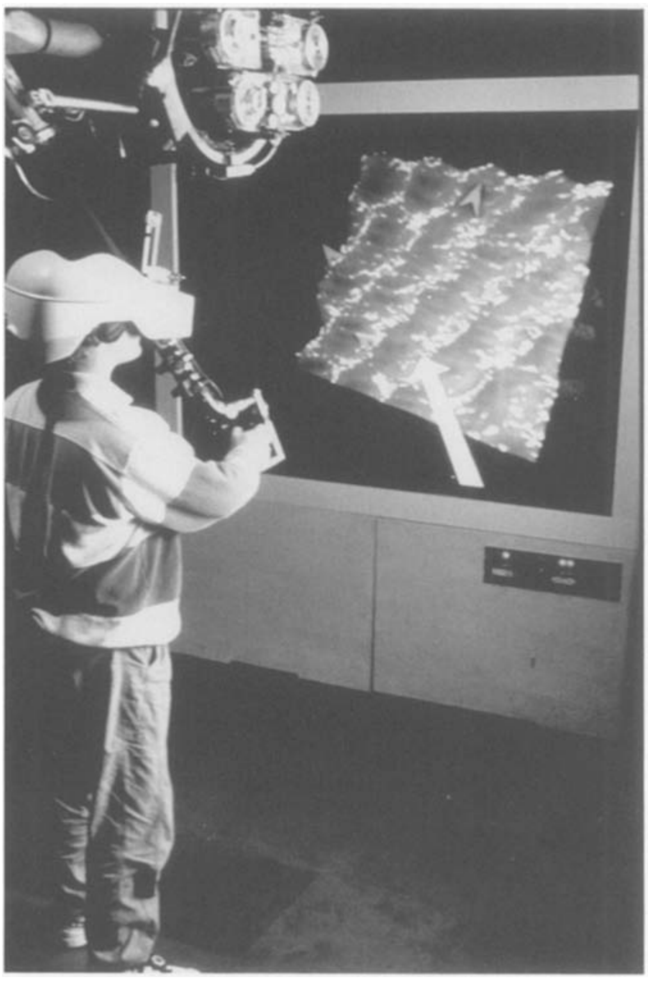


Fig. 9. A researcher at the University of North Carolina at Chapel Hill, Department of Computer Science, uses a head-mounted display and force-feedback ARM to explore a graphite surface at atomic resolution with a scanning-tunneling microscope. (Photo: Alex Treml. Courtesy of Linda Houseman.) Even in scientific applications, virtual reality retains and utilizes the aesthetic of escape, whose historical roots and pictorial parallels lie in romanticism.

References and Notes

1. The term "ghetto" is from Margaret Benyon, "Do We Need an Aesthetics of Holography?" *Leonardo* 25, No. 5, 415 (1990).

2. Erwin Panofsky's *Idea: A Concept in Art Theory* is still the place to begin. See further Howard Stein,"Logos, Logic, and Logistiké: Some Philosophical Remarks on [the] Nineteenth-Century Transformation of Mathematics," in Herbert Feigl, ed., *Minnesota Studies in the Philosophy of Science* 11, *History and Philosophy of Modern Mathematics* (Minneapolis, MN: Univ. of Minnesota Press, 1988) pp. 252ff. Some interest in visualization has taken its methods from scientific empiricism, but a great deal more has been concerned with the proper form of Kant's claim that there is an a priori intu-

ition of the three Euclidean axes. Bertrand Russell's *Foundations of Geometry*, an early work, concerns replacing Euclidean geometry with projective geometry as the basis of intuition. Rudolf Luneburg's *Mathematical Analysis of Binocular Vision* (Princeton, 1947) posits a "personal constant" *K* such that each individual might experience the world in a slightly different way: my space may be a little more Euclidean, yours may be tinged with Lobachevskiian transgressions.

3. Barry Cipra, "Cross-Disciplinary Artists Know Good Math When They See It. . . ," *Science* **257** (7 August 1992) p. 748. Another puzzle is to visualize how a cube, when rotated around an axis that passes through two opposite corners, can look the same every one-third rotation.

4. See R.M. Friedhoff and T.W. Benzon, *The Second Computer Revolution: Visualization* (New York, 1989), and K.A. Frenkel,"The Art and Science of Visualizing Data," *Communications of the Associations for Computing Machinery* **31**, No. 2, 111–121 (1988). Further references are in Richard Wright, "Computer Graphics as Allegorical Knowledge: Electronic Imagery in the Sciences," *Digital Image—Digital Cinema* SIGGRAPH '90 Art Show Catalog, Supplemental Issue of *Leonardo* (1990) pp. 65–73.

5. Richard A. Kerr, "Do NASA Images Create Fantastic Voyages?" *Science* **255** (27 March 1992) p. 1637; and Richard Mark Friedhoff and William Benzon, *The Second Computer Revolution: Visualization* (New York: Abrams, 1989).

6. Faye Flam, "In Search of a New Cosmic Blueprint," *Science* **254** (22 November 1991) pp. 1106–1108; and Margaret J. Geller and John P. Huchra,"Mapping the Universe," *Science* **246** (17 November 1989) pp. 885, 897–903 and cover.

7. Phil Mercurio has produced images with transparent components at the San Diego Supercomputing Center. See *Science* **255** (13 March 1992) p. 1358.

8. From Erwin and Warren E. Pickett, "Theoretical Fermi-Surface Properties and Superconducting Parameters for K3C60," *Science* **254** (8 November 1991) pp. 842–845.

9. The printout, which requires false color to be fully legible, highlights a puddle of bitumen in the skull and a palm stalk between the spine and the brain (just visible at the bottom of the plate).

10. See Michael Halle et al., magnetic resonance imaging (MRI) of radiation treatment probe simulation with isodose contours, 1992 SIGGRAPH stereo slide set (No. 15/16).

11. This is explored in my essay "The Drunken Conversation of Chaos and Painting," *M/E/A/N/I/N/G* **12** (1992) pp. 55–60.

12. Peter Galassi, *Before Photography: Painting and the Invention of Photography* (New York: Museum of Modern Art, 1981).

13. W. Leitzmann, *Visual Topology*, M. Bruckheimer, trans. (London: Chatto & Windus, 1965) 11–15. "Problems of representation" are explored here, but only as far as questions of overlapping lines and schematic trees.

14. The relation between the two is explored at length in my "Poetics of Perspective," forthcoming at the time of writing from Cornell Univ. Press (1994).

15. For an alternate account, see Hubert Damisch, *L'Origine de la perspective* (Paris, 1987), forthcoming in translation from MIT Press.

16. See Robert Minsk et al., pictures of an atomic force microscope pulling up from a lubricated surface, 1992 SIGGRAPH stereo slide set (No. 67/68).

17. Perspective view of a cube from A.J. Hanson, P.A. Heng, and B.C. Kaplan, "Techniques for Visualizing Fermat's Last Theorem: A Case Study," in Arie Kaufman, ed., *Visualization '90*, Proceedings of the IEEE Computer Society and SIGGRAPH (Los Alamos, NM: IEEE Computer Society Press, 1990) p. 99, Fig. 3.

18. John R. Wallaca, "Trends in Radiosity for Image Synthesis," in Kadi Bouatoch and Christian Bouville, eds., *Photorealism in Computer Graphics*, (Berlin and New York: Springer-Verlag, 1992). See the color plates of a Vermeer painting, Chartres, and an invented interior.

19. The dependence of traditional-looking scenes on software that works in nontraditional ways is brought out by examining the steps that lead to the generation of an image. See, for example, the interior generated by six faces of a cube in Steve Upstill, *The RenderMan Companion: A Programmer's Guide to Realistic Computer Graphics*, 2nd Ed. (Reading, MA.: Addison-Wesley, 1990), Plates 14 and 15.

20. R.L. Hollis, S. Salcudean, and D.W. Abraham, *Toward a Telenanorobotic Manipulation System with Atomic Scale Force Feedback and Motion Resolution* (Yorktown Heights, NY: IBM, 1990) cited in Howard Rheingold, *Virtual Reality* (New York, 1991).

21. See for example Joan Truckenbrod, "A New Language for Artistic Expression: The Electronic Arts Landscape," *Electronic Art* supplemental issue of *Leonardo* (1988) pp. 99–102.

22. In discussions, it has been proposed that pantographs and mechanical perspective apparatuses might also be examples. But there, the operator does not have to watch the drawing develop, since she is only tracing something that has already been drawn (a pre-existing sketch or scale drawing).

23. This implies a certain pedagogic prescription. If these instances can be generalized, they would suggest that instruction in computer graphics should largely be done by painters, historians and critics, with computer graphics experts providing technical advice. In my opinion the staff in computer labs and "Art and Technology" departments should not critique their students' work. This should obtain until the graphics experts can substantiate their claim to be teaching a new medium.

24. From Jose Maria Carrascal Muñoz, *Francisco Zurbarán* (Madrid: Ediciones Giner, 1973) p. 103.

25. Slide sets and conference proceedings may be ordered from ACM SIGGRAPH, 11 West 42nd Street, 3rd Floor, New York, NY 10036.

26. From Paolo d'Ancona, *Tiepolo in Milan, the Palazzo Clerici Frescoes*, L. Krasnik, trans. (Milan: Edizioni del Millone, 1956) Plate 16.

27. See [25].

28. From John Gregory and Irena Zdanowicz, *Rembrandt in the Collections of the National Gallery of Victoria* (Melbourne: National Gallery of Victoria, 1988) Fig. 40.

29. From Leon Battista Alberti, *Ten Books on Architecture*, Cosimo Bartoli and James Leoni, trans. (London: Alec Triani, 1955), Plate 9.

30. From A.J. Hanson, "Techniques for Visualizing Fermat's Last Theorem: A Case Study," in *Visualization '90* (Los Alamos, NM: IEEE Society Press, 1990) Fig. 3. Generated for the author on Mathematica.