From Solid to Map: Transformations of Realism in Computer Graphics, 1963-1978

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"We live today in the age of partial objects… We believe only in totalities that are peripheral. And if we discover such a totality alongside various separate parts, it is a whole *of* these particular parts but does not totalize them; it is a unity *of* all of these particular parts but does not unify them; rather, it is added to them as a new part fabricated separately."

Gilles Deleuze and Félix Guattari, *Anti-Oedipus*

Introduction

There seems to be a dichotomy in media studies of computer graphics, where an analysis either conceives of computer graphics in terms of the screen as its formal and phenomenological limit, or it conceives of computer graphics as fundamentally deriving from the materiality of the computer.[1] Curiously, it is also possible for each of these poles to fold back into one another, or to swap places as two sides of the same attempt to define what computational media really is. For an example, see how this idealism/materialism organizes an analysis by Lev Manovich of "new media" in his classic *The Language of New Media*, where the computer screen lies within the older tradition of the representational frame yet challenges it through its new digital form.[2] What is at stake is an understanding of what the object *essentially* is. I suspect that this debate is an utterly *productive* work lying at the intersection of the academy and the market, where a theory of computational media inadvertently derives its own value and meaning from the success of the industries and objects which it theorizes about. Along this whole machine is produced a useful language, a way of speaking that hardly can escape from the images our world produces about itself,[3] including images of totality.

"Realism" is a totalizing notion, used both in computer graphics marketing and in academic writing about computer graphics, that seems to actively abolish its own history. Within this perspective the whole of computer graphics up to our own time has always been directed toward the more perfect simulation of the real. In opposition to this, I think that the discourse of realism is generated through the operation of multiple parts in tandem, including mass culture, industrial forces, and the academy. As such, I consider the production of realism to have a profoundly historical character, and to have left visible documentary traces. In this paper I am interested in presenting a history that attends to these traces as they appear in the computer graphics literature and as they reveal differences in the use of computer graphics knowledge. My method has been to move chronologically through the trails of referenced works in the scientific literature, noting at what times the production of knowledge seems to have undergone a transformation in its concepts, techniques, and uses, which is illustrated during this period quite clearly.[4]

The central institution of this history is the Computer Science Department at the University of Utah, featuring in recent narratives[5] as critical to the development of computer graphics in the late 60s and 70s. In this paper it is notable above all as a site that reflects the beginning of a new use of computer graphics knowledge, exhibiting changes in the institutional form of graphics research and in the relationship between federal funding of research and the market. I will first look at a few papers from MIT Lincoln Laboratory in 1963 that are referenced in the transitional computer graphics literature of the 60s, arguing that during this time the simulation of depth was the dominating interest in computer graphics research. I will then look at the transitional period, noting that despite the invention of computer-rendered halftone shading in 1966, it was not until the early 70s that we see the flourishing of a form of knowledge with new concerns. I will review how computer graphics research was established at the University of Utah and how it became increasingly related to production within the ramifications of a nascent computer graphics industry. Then, I will proceed chronologically through the important literature produced there during this period in parallel with the contract progress reports which were submitted by David Evans semiannually to secure funding from ARPA for the Computer Science Department at the University of Utah.[6] This will allow us to see what changed in the conditions for computer graphics knowledge production, and how the earlier formation concerned with the correct organization of geometry and simulation of depth was dissolved according to a new concern for parameterized elements, mappable surfaces, and articulated space. This new form of knowledge is described further in an analysis of the classic literature produced at the University of Utah in the 70s, though I pass over important developments in digital image processing, anti-aliasing, and shadows, focusing instead on animation, lighting models, and parametric mapping. Finally I will summarize the state of computer graphics knowledge in these areas by the end of the 70s and describe the use of realism in computer graphics.

Predecessors, 1963

Published in 1963, Lawrence Roberts's Ph.D. thesis *Machine Perception of Three-Dimensional Solids*[7] is really the first paper that is widely referenced in the computer graphics literature in the period preceding the establishment of the Computer Science Department at the University of Utah. But it is natural to include two other papers published several months before: Ivan Sutherland's Ph.D. thesis, the now-famous *Sketchpad, A Man-Machine Graphical Communication System*,[8] and Timothy Johnson's M.S. thesis *Sketchpad III, Three Dimensional Graphical Communication With a Digital Computer*.[9] They all exhibit a certain attitude towards computer graphics. What characterizes these three papers is the program of man-computer symbiosis as set out by J.C.R. Licklider, who was director of the Information Processing Techniques Office (IPTO) of the Advanced Research Projects Agency (ARPA) from its inception in 1962 to 1964. As described in a 1960 article by Licklider, man-computer symbiosis presented the opportunity to create a more powerful form of thinking and decision-making that was impeded by current problems in the state of computer equipment and the organization of its relationship to man.[10] Licklider justified the development of man-computer symbiosis through a time-and-motion analysis of technical "mental" work, noting the amount of time spent on merely clerical or mechanical work. In doing so, he linked symbiosis to techniques of scientific management and industrial efficiency that had been theorized since the late 19th century. Two of the most important requirements for man-computer symbiosis as it applied to early computer graphics were real-time cooperation, and intuitive display and control such that the computer would function like “another engineer” who was also “a precise draftsman” and “a lightning calculator,” among other helpful roles.

Sutherland’s *Sketchpad* references Licklider’s writings and includes features that directly address issues of man-machine communication in terms of interactive computer graphics. It was a system capable of real-time CRT input and display of graphical “symbols” that could be constrained, composited, and copied. Besides auxiliary banks of toggle switches, push buttons, and knobs interfacing to the TX-2, the system incorporated the usage of a light pen. Sutherland was impressed by the computer’s capability for visualizing and modifying complex relationships between parts in real time, impossible when using conventional pencil and paper methods. He first encountered this possibility with what he called “linkages,” or copies of graphical symbols arranged into an interconnected lattice, in which small constraint modifications would produce dramatic structural changes. The potential for visualizing abstract mathematical relationships was something that he would reiterate two years later as the new head of the ARPA IPTO in an article titled “The Ultimate Display.” In it he describes the potential for the computer to familiarize man with physics and mathematics, with abstract relationships between things, where “such knowledge is the major promise of computer displays.”[11]

Johnson’s *Sketchpad III* builds on Sutherland’s system, extrapolating its basic techniques into a three-dimensional context where the user can draw wire frames in depth by rotating the drawing plane and view through a shaft encoder. In this paper we see the first appearance of certain problems and attitudes toward them that reveals concerns that endure all throughout this early period. Central among these concerns is the simulation of depth. Johnson enumerates three visual means of producing depth perception: “1) the binocular effect, 2) the perspective effect, and 3) the obstruction of rearward surfaces by opaque, forward high-lighted surfaces.”[12] In the same paper, Johnson compares the binocular effect, a technique known since the 19th century in stereoscopy, as an alternative to direct three-dimensional display by projection onto a rapidly rotating translucent screen, clearly illustrating the character of early computer graphics knowledge. The perspective effect, which refers to various means by which parallel edges of objects not parallel to the picture plane seem to converge to a point in the distance,[13] was the only depth-producing technique implemented in Johnson’s system, and it is mechanically produced through the application of matrix mathematics to graphical data. The last means of producing depth perception on Johnson’s list involves two problems that will become increasingly central and then undergo a fundamental transformation in the University of Utah literature. The requirement of “high-lighted surfaces” is later formalized as the problem of shading, and the necessity of an “obstruction of rearward surfaces” refers to the critical problem of hidden-line and hidden-surface removal.[14]

Roberts did his graduate work alongside Sutherland and Johnson at MIT Lincoln Laboratory. His influential *Machine Perception*, besides being a seminal text referenced in nearly every major computer graphics paper of the 60s, is also one of the first important papers in computer vision as we understand it today. It is concerned with the “machine recognition of pictorial data,”[15] and mostly references texts in artificial intelligence and the psychophysiology of vision. It describes a system for the replication of planar objects in photographs on the computer and the subsequent visualization of this data. As a paper on computerized vision, it reveals in a particularly stark way the assumptions made in this early period about the computer's capacities in producing visual knowledge and the nature of this knowledge. Again, it is a knowledge concerned with the correct relationships between elements in depth. Roberts assumes that "the human visual field is the result of a projective transformation and the shapes perceived are independent of this transform,"[16] and that therefore one could arrive at the 3D data of these shapes through an inverse transformation of the 2D visual field. Formalizing this intuition, his system scans a photograph, computes the edges in the image, reconstructs polygons from the edges, and then extrapolates 3D models by decomposing the polygons into simple predefined models with matching topologies and projections and progressively "subtracting" them from the image. To display the reconstructed 3D objects, the system draws their visible contours, providing the first solution to the hidden-line problem based on mathematics determining whether or not a line segment lies within a volume. *Machine Perception* exhibits the general identity in the literature of this period between human vision, the photographic camera, and projective geometry as mechanized in computer graphics.

Transformation, 1967-71

In 1965, the president of the University of Utah invited David Evans to establish a Computer Science Department within the School of Engineering. Federal funding of basic research in computer science had grown dramatically during the Cold War through the establishment of ARPA and the IPTO, the latter being directed in 1965 by Sutherland and then by Robert Taylor from 1966 to 1968. After Evans accepted his new position in 1966 as Director of Computer Science and Computer Operations, he was able to secure significant funding from ARPA that was necessary to build a computer science division from scratch. In cooperation with Taylor, Evans planned on transforming the University of Utah into an IPTO-designated Center of Excellence specializing in computer graphics, making it one of the premier institutions in the United States for graphics research and attracting to it a focused stream of funding from ARPA. Evans was successful in recruiting excellent faculty and graduate students, and he allowed them to pursue interesting research in computer graphics and other related topics with little oversight, a managerial style inherited from the one prevalent at ARPA.

Not long after the program was established, Evans arranged with Sutherland in 1968 to co-found the Evans & Sutherland Computer Corporation (E&S), introducing a new dynamic into computer graphics research. As the first firm in the United States to commercialize this kind of research and because of its close relationship with the University of Utah, it had a fundamental effect on the character of the most advanced work being done in graphics. It employed graduate students and recent graduates trained by the Computer Science Department at the University of Utah,[17] was physically established on the University's Research Park[18] and even had networked access to the computer science division's equipment on campus.[19] In fact, the Computer Science Department at the University of Utah functioned as an apparatus attached to E&S by which ARPA federal funding was transformed into industrial investment through the creation of marketable technologies and a highly-trained supply of scientists and engineers working with state-of-the-art computer graphics.[20] Some of the research topics and applications developed through ARPA funding at the University of Utah's Computer Science Department included architectural design, mechanical and electrical design, medical simulation, scientific visualization, and by the early 70s, animation and movies. Through E&S, academic scientific research became commercial scientific research, and the development of computer graphics technology for the market would only expand from this period on, profoundly transforming computer graphics knowledge.

Work that would culminate in the first important computer graphics paper at the University of Utah was mentioned in a 1966 progress report for the ARPA contract titled "Graphical Man/Machine Communications." Evans described the development of halftone-shaded display of objects, writing that "such a representation of the object is of basic value, because it corresponds to the representation of the real world on the human retina."[21] "Half-Tone Perspective Drawings By Computer"[22] by Chris Wylie, Gordon Romney, David Evans, and Alan Erdahl was published the next year. The paper introduces for the first time the concept of triangulation and a technique for halftone shading, where the intensity over each triangle is linearly interpolated from values at the vertices derived in each case by their distance to the view point. Perhaps the most important aspect of the algorithm introduced is that it can solve the hidden-surface problem in linear time with respect to the number of objects and the resolution of the display. It achieves this by sorting triangles along scan lines across the view plane according to depth before writing the closest triangle's intensity to the display, and it is the first hidden-surface algorithm to perform this kind of sorting and scanning. The authors also provide a list strikingly similar to Johnson's from three years ago of things that "apparently help the viewer's ability to 'feel' the overall structure of a three-dimensional object: 1) binocular (or stereo) vision, 2) elimination of the hidden surfaces, 3) recognition of distance and shape as a function of illumination (or shading), and 4) real time movement."[23] It is critical to note that despite its novelty, the authors still use half-tone shading "to give the illusion of depth (or distance) and indicate spatial relationships."[24] It is also interesting to see in this early paper that real-time movement is explicitly predicted along the lines of a more efficient hardware implementation of graphics algorithms,[25] which is continuously developed from the 70s on.

The importance of computer graphics research done at the University of Utah led to a centrifugal ecosystem in which authors consistently referenced specific papers that had either been produced at the University of Utah or ultimately relied on work done there. It is striking to see how much of a break is implied by the early papers produced at the University of Utah, in that no particular "peripheral" papers are really central, though several do reappear somewhat often. The few relatively important papers[26] from the periphery during the transitional period of the late 60s remain within the early regime of computer graphics knowledge. This is the case even after the character of research began to change at the University of Utah toward the end of the decade, which suggests the significance of the unique conditions there. An example from the periphery during this period can be found with Arthur Appel at IBM. He published a paper in 1967 on hidden-edge removal, and its description of the current state of computer graphics is telling. It states that line drawings are useful not only because of their economy, but also for "the great information density obtainable," and that correct hidden-line removal is necessary "in order to convey a realistic impression of an object."[27] We will see this situation occur again, where an author justifies the current state of the field using the term "realism," here meaning above all a vivid and correct depth impression, in ways that reflect the fundamental conditions of computer graphics knowledge at the time.

Appel also published another paper the next year. It contains one of the first descriptions of the concept of "ray-casting" and addresses halftone shading and shadows. Again, although the capability to produce shading had just recently been developed, it was still understood in terms of enhancing the space and depth of solids, of exploiting the "value of of shading and shadow casting in spatial description,"[28] rather than in achieving the kind of realism desired by the mid 70s. As a case in point, the ray-casting discussed in this article, rather than progressing from object to object in order to collect the correct light intensity reflected in the global scene, instead produces a uniform shade on the first surface hit by a light while throwing everything behind it in a starkly outlined shadow. Appel's paper also references another article[29] that, besides providing a technique for generating stereographic pictures, represented shading through more or less dense sets of parallel lines on different surfaces, a technique quite foreign to the later shading of the 70s, which is derived from a realism that recognized surfaces as parametric and essentially varying across space.

By 1969, the ARPA progress reports detail the development of new projects in CAD, physiological information processing, and "colored halftone perspective pictures being used to represent complex multivariable situations."[30] They also mention one of the next milestone papers in the University of Utah literature, which began as a technical report[31] and was expanded the next year under the title "A Hidden Surface Algorithm for Computer Generated Halftone Pictures."[32] They were written by John Warnock, originally a mathematics Ph.D. who was poached by Evans for the Computer Science Department.[33] "A Hidden Surface Algorithm" provides a powerful "image-space" solution to the hidden surface problem. The projected image is defined, to the lower limit of the display resolution, in terms of areas that are either empty or not, and any non-empty areas are recursively analyzed if they contain multiple surfaces determined to be visible by their edges and order in depth. Warnock's paper also provides the first ever extended analysis of shading models, introducing the RGB color model and the concept of a specular component. Notably contrasting with the later "physical" models of global illumination in the 80s, Warnock admits that his models "have been constructed on empirical considerations and should in no way be regarded as models for colorimetry, optics, or psychophysics."[34] Photorealism is not yet the point. But the graphical object is becoming like a set of parameters.

Warnock's interesting paper seems to mark the beginning of a profound shift in the treatment of color and light in computer graphics. In it he states that "present day equipment makes it impossible to achieve the pictorial realism that a graphic artist can attain," and that it would be desirable to control "intensity, color, and location of light sources; reflectance, surface texture, and coloring of the objects; and general illumination and atmospheric interferences in the picture field."[35] This is a surprising development when considering the kinds of statements made in the previous literature. While a reference to "direct and diffuse lighting, atmospheric diffusion, back reflection, the effect of surface texture, tonal specification, and the transparency of surfaces"[36] was present the year before in Appel's article under the rubric of "chiaroscuro" painting techniques à la Rembrandt and Reubens, and the notion of "texture gradient" from psychophysiology even briefly appears as far back as in Roberts's *Machine Perception*,[37] the ultimate purpose in both cases was to clearly distinguish surfaces in order to represent objects in depth. Now, the use of color and light have become ambiguous in that respect, and any traces of the discourse on depth are conspicuously absent. It seems that computer graphics was beginning to enter a cultural register in which it could be compared to "traditional" forms and conceptions of art, similar to how film was compared in the early 20th century[38] right as it was establishing itself as a large-scale entertainment industry dominated by American studios. Indeed, the relationship between art and the computer had already been explored and legitimized by the late 60s. One of the earliest major exhibitions to include computer art, *The Machine as Seen at the End of the Mechanical Age*, was held at the end of 1968 in the Museum of Modern Art.[39] Both computer graphics's comparison to painting and its appearance within commercial film by the mid 70s was the result of a fundamentally new use for computer graphics within the horizon of production.

At the start of the new decade, Gary Watkins submitted *A Real-Time Visible Surface Algorithm*[40] for his dissertation. The paper describes a hidden-surface solution using a scan-line and depth-sorting method that generates visible segments of a relatively large class of planar polygons. Implemented in hardware as the "Watkins Processor," it provided the technical basis for the most advanced real-time dynamic shading at the University of Utah until the algorithm was superseded in 1974. The ARPA progress reports following the paper's publication emphasize the development of the system in hardware as a vanguard technology, stating in May of the next year that "uses for this system are unlimited," with its applications including "environmental (world, space, flight, molecular, etc.) simulation," and that the "current state of the art just now enables the construction of such hardware since it uses semi-conductor memories in the 200 nanosecond cycle range."[41] This optimism in advanced computer graphics within the evolving economics of computing was concomitant with the development of a ramified, "unlimited" set of applications ultimately destined for the market, and it increasingly characterizes the way researchers began thinking about computer graphics and the way the nascent industry spoke about itself.

In the June ARPA progress report of the same year, eager notice is given of a new technique used for shading objects that restored "the apparent smoothness of the surface."[42] This refers to Henri Gouraud's graduate work which was published during the same period in the truly pivotal *Computer Display of Curved Surfaces*.[43] Gouraud found this work necessary because line renderings of parametric surfaces were misleading and Mach banding in newer techniques heightened the distinction between adjacent shaded planar polygons, which was the only class of geometry used in the last three drawing algorithms developed at the University of Utah. Gouraud's algorithm made "it possible to represent with great realism a large new class of objects"[44] including cars, airplanes, and particularly the human face and body, by approximating surfaces with small planar polygons, then interpolating color across each polygon using the intensities at its vertices calculated with Lambert's cosine law. For the first time, computer images with smooth shading were possible. It is also significant that at this time Roberts's *Machine Perception*, which had been so important in the previous period, generally and completely falls out of the referenced literature. The importance of Gouraud's work in marking the general transformation of computer graphics knowledge by this time can hardly be overstated, and ideas that first appeared here or in the couple of years prior at the University of Utah dominate graphics research in the 70s.

Relationships within the whole field of concepts in computer graphics are reconstituted according to the new use of graphics. For example, the difference in shade between two adjacent surfaces, emphasized by Mach banding and subsequently “solved” by smooth shading, was precisely what the earlier computer graphics praised as producing a depth impression. It is the shaded approximated curved surface, used in marketable applications for design, simulation, and animation, that necessitates smooth shading. Additionally, Gouraud’s algorithm requires the points approximating a surface be chosen such that the polygon normals, in conjunction with the lighting model, achieve the correct shade variation of the surface. Rather than shading being used to show the solidity of geometry, for the first time geometry ought to be specified in order to produce the correct color effects. Indeed, one of the applications suggested in a 1972 ARPA progress report uses “polygons which are to be viewed only from a distance,” where “color can be used to approximate objects which need not be shown in detail.”[45] These reversals signify the beginning of a period in computer graphics where researchers produce knowledge about surfaces and the raster as maps of parameters including color and orientation, and where the normal attains status as the privileged geometrical indicator. Consider that one of the applications suggested by Gouraud is visualizing stress in a sheet of metal through the strategic construction of normals “plotting on the picture an intensity which bears no relation to the actual shape of the object represented.”[46] The dissolution of the object into many formally identical, small, arbitrarily parameterized elements is reflected in the importance of parallelism to algorithms that would allow efficient hardware implementations, such as in the Watkins Processor. *Computer Display of Curved Surfaces* marks the beginning of a period that produces what I consider to be the “classic” computer graphics literature, techniques of which are still taught in academic contexts, supported by standardized industry hardware, and underlie the majority of computer graphics systems today.

Maturation, 1972-78

We see the word “animation” suddenly appear in the last ARPA progress report of 1971, where the term refers to graphics languages that are capable of producing and controlling models. Despite the fact that these functions had already been necessary in the contexts of CAD and visualization, the report uses the new term when describing projects on an “animation language” and on “distorting surfaces.” Included are pictures of a smooth-shaded hand and face in different poses.[47] This work would be published the next year in the ACM proceedings as Edwin Catmull’s “A System for Computer Generated Movies”[48] and Frederick Parke’s “Computer Generated Animation of Faces.”[49] Catmull’s article describes a language for defining kinds of motions for each object, or a “group of polygons that will transform together,”[50] and for building a hierarchical body out of objects. Each object is hierarchically attached to another object by a pivot that passes on the parent’s transformations to the child. Parke’s article describes a technique that would later become known in computer animation as blend shapes, where the vertices of a model are interpolated between two different keyframes, or states. Through animation, computer graphics space was understood as articulated instead of cohesive. In Catmull’s case, objects are transformed as a hierarchy articulated through pivots, and in Parke’s case, the model has a different coordinate system from the view in order to interpolate the model's vertices separately from more general transformations. It is also remarkable how the measurement of real objects in order to simulate them on the computer was becoming common. Catmull used a digitized version of his own hand for an example, and Parke used photogrammetry to create his face model, similar to Gouraud from the year before. Indeed, that same year Sutherland would task his students to measure something instantly recognizable and iconic and the students chose a Volkswagen Beetle, partly because it was "a symbol of global culture."[51] Techniques for specifying animations would only become more important from this time on. As Catmull put it, computer pictures and movies had "recently caught the public eye," and his hand would make its way in 1976 into *Futureworld*, the first film to have 3D computer graphics. Remember however that the goal is not yet the photorealism of the 80s. Here, simple mathematical functions are used to drive motion, distinct from the physical models that would appear only later.

In the next couple of years, two algorithms containing related solutions to the hidden-surface problem would appear. The first came from outside the University of Utah and was published in 1973 as "A Solution to the Hidden Surface Problem"[52] by Martin Newell, Richard Newell, and Tom Sancha at the CADCentre in Cambridge. The second was Catmull's dissertation work at the University of Utah published in 1974 as *A Subdivision Algorithm for Computer Display of Curved Surfaces*.[53] The first article introduced what is now known as the Painter's Algorithm, where basically polygons are sorted in z-depth and then "painted" from furthest to nearest on a screen map simulating the raster image in memory,[54] overwriting whatever was present in the drawing "area," or combining with it for a transparency effect. The authors of that article note that writing faces using a separate "hardware screen map" instead of core memory would remove a large part of the computational load,[55] suggesting the influence of increasingly cheap and quick semiconductor technology on algorithm design. Catmull's paper describes a hidden-surface removal method inspired by Warnock's image-space technique from five years ago, where a specific class of analytical surfaces or patches are subdivided into sub-patches until each sub-patch projected onto the raster covers one raster-element. The hidden-surface problem is solved here through the use of a "frame-buffer," or a "memory large enough to store all of the intensity values" of the raster image. This is the hardware screen map suggested by Newell et al., but instead of presorting the surfaces as in the earlier article, Catmull's method writes the depth of each sub-patch along with its intensity to the frame-buffer so that a single depth comparison is sufficient to determine hidden sub-patches. This is an extremely powerful technique and is still the basis for the vast majority of hidden-surface determination as it is standardized in hardware today.

But Catmull's paper provides even more insights besides this. The parametric representation of the analytical surface suggests multiple ways of generating the intensity at a point. The methods of using surface normals, of applying an "abstract" intensity function of parameters u and v, and of modifying existing intensities for transparency were already known in the literature. The most interesting and new method discussed by Catmull is mapping the intensities from an external picture or image onto a surface, implying related techniques that would soon be called texture mapping and environment mapping in an article by James Blinn and Martin Newell. Their "Texture and Reflection in Computer Generated Images"[56] appeared in 1976, and it was the first paper from the University of Utah published in the SIGGRAPH proceedings. In it the authors describe improvements to the original technique of texture mapping by blur filtering the image in order to attenuate aliasing effects produced by digital sampling when mapping it onto the surface. Environment mapping, or simulating reflections of the environment on a surface, is the more novel application described in the paper, and it relies on the fact that a subdivided analytical surface provides accurate normals at each renderable picture element (or what had been previously called a "raster-element"). The concept of environment mapping is illustrated in the paper as a projection of each picture element normal onto a sphere "painted" with the environment, mapping a location on an object's surface to a coordinate on the environment texture.

One of Blinn and Newell's examples included smoothly-shaded specular highlights, an effect that had been developed a year earlier by Bui Tuong Phong. Published in 1975, Phong's "Illumination for Computer Generated Pictures"[57] marks the beginning of a certain attention to the physical basis of lighting models which continues into the 80s. Inspired by Newell et al. and Warnock's representation of specular highlights and Gouraud's smooth shading, while addressing their inability to handle shade discontinuities, Phong describes a "physical model" that includes a diffuse component based on the angle between the surface and light, and a specular component that produces highlights based on the angle between the light reflection and the viewer. The intensity across a surface is then determined by interpolating values between the normals of each vertex that are used in the shading equation, rather than interpolating the intensities themselves as in Gouraud's method. Most previous shading models, even going back to "Half-tone Perspective Drawings" in 1966, conceptually placed the light source at the same position as the eye in order to sidestep the problem of generating correct shadows. While Phong does not address the correct generation of shadows, he does cleave the light source from the eye and leaves their relationship variable, implying the notion of autonomous light sources that interact with the position of the viewer to produce visible effects. This prepares some of the technical and conceptual elements used by methods in the 80s that determine global illumination within a space activated by light sources, objects, and an observer.

In 1977 Blinn published a related paper on shading titled "Models of Light Reflection for Computer Synthesized Pictures."[58] The article provides an augmented Blinn-Phong model now in standard use, which incorporates an ambient component and uses the "ideal" normal situated halfway between the light and eye compared to the surface normal in order to calculate the specular component. But perhaps the most interesting aspect in the paper is the first appearance of using modern experimental optical research in order to produce a physically-based lighting model, distinct from the so-called "empirical" models based on earlier geometrical optics. The effects created by this model "are somewhat subtle and are apparent only during movie sequences,"[59] suggesting the importance of new modes of viewing computer graphics. In the physical model described, the surface is assumed to be composed of more or less randomly-oriented micro-facets that ideally reflect light, and the specular component is determined by a parameter representing the distribution of micro-facets correctly reflecting light into the eye, the surface's smoothness, while the diffuse component is determined by a parameter representing internal scattering on the surface, the surface's roughness. Blinn also introduces an interesting application inspired by earlier work based on mapping, whereby an image containing parameter values of the surface's smoothness or roughness is mapped onto the surface in order to produce textural effects.

This paper would be followed in 1978 with "Simulation of Wrinkled Surfaces,"[60] also authored by Blinn, who had by this point moved on from the University of Utah to the Jet Propulsion Laboratory at Caltech. Here we see a further development of techniques ultimately based on the parametric character of a surface that functions as a map for arbitrary values. Dissatisfied with the unnaturally smooth look of an object when attempting to simulate surface texture with conventional texture mapping, Blinn introduces what is now known as bump-mapping, where an image of values that define small perturbations of the surface is used to derive artificial normals. When the lighting model is applied to these artificial normals, the result is an image of the rough object that seems to have correct geometrical variation across its surface. Blinn also suggests a kind of "environmental-depth" mapping using the raster, where the z-values of the projected picture retained in the depth buffer can be itself mapped as a texture onto an object. Interestingly, Blinn references an article[61] that uses computer graphics to reconstruct a relief image of the earth from a large set of contour data taken by surveyors on the ground. This is a form of digitization not unlike those used to replicate a hand, a face, or a car on the computer that we have seen with Catmull, Parke, Gouraud, and Sutherland.

Blinn's departure to the Jet Propulsion Laboratory was symptomatic of the exodus in the late 70s of important researchers to places including Xerox PARC and NYIT.[62] This was due in part to the Mansfield Amendments passed in 1969 and 1973 which prohibited military and ARPA funding of projects without direct military application, and which made financial support for the Computer Science Department at the University of Utah increasingly harder to attain over the decade. We have seen that in the fifteen years since 1963 there had been a rapid transformation of computer graphics knowledge in concepts, techniques, and more fundamentally, uses. No longer "about" the realistic and correct representation of solids in space through the depth impression, computer graphics had taken as its object the realistic and correct simulation of parameterized surfaces and animations in space. There had been a great proliferation of techniques in the literature for treating the surface as a map, as exemplified in Phong and Blinn. There were methods for defining motion within articulated space, as in Catmull and Parke. And the raster image had become an important technical-conceptual tool and the standard means supported by hardware of representing graphics. We also have seen the forerunner elements of a knowledge concerned with physical simulation on the computer.

To close this period of development in the 70s, we can mention a paper published in 1980 by Turner Whitted titled "An Improved Illumination Model for Shaded Display."[63] This paper contains the first major description of a method for global illumination through ray-tracing, remobilizing concepts that had been in development since Warnock's first analysis of a computer graphics model for lighting in 1969. Notably, it integrates the many effects which had been pursued in terms of different applications of maps and parameters of surfaces into a single physical illumination model, but still only in terms of classical ray optics. We also witness a kind of tenacious a-historicizing effect exhibited in the production of computer graphics by this time when Whitted writes that "since its beginnings, shaded computer graphics has progressed toward greater realism."[64] This statement buries the great differences inflecting the historical development of computer graphics, which our analysis of the literature has revealed.

Postscript: The Progression of Realism

What then is the role of this progression toward realism in our world? A hint toward answering this question appears in an article published by Blinn and Newell in 1977 with the title "The Progression of Realism in Computer Generated Images."[65] The paper reviews recent advances and new tasks in achieving realism by way of a typology describing the major areas of focus: scene geometry, surface properties, lighting models, transparency, shadows, aliasing, display device resolution, and motion. The paper also provides a short history of the use of realistic graphics, where the first motivation for producing "photograph-like images" had been in "flight simulation," but then developing mostly in CAD and animation as "these applications were not so tightly constrained by speed considerations, and so more effort could be devoted to realism."[66] We have seen how the development of such applications at the University of Utah destined for the market through E&S created a forcing-house for advances in computer graphics involving surfaces and motion. This allowed commercial technology to successfully compete on the market, not only cutting costs associated with conventional methods but also introducing a new and desirable ability to produce effects impossible otherwise. The authors suggest a Turing-like test, where a measure of realism would be to see how long it takes for someone to detect that a picture was in fact computer-generated. They admit that "an observer's performance will be affected by his knowledge of current state-of-the-art image synthesis techniques,"[67] thus implying a dynamic in computer graphics still present with us today, where new realistic effects make old computer graphics look worse in comparison. We can refer to this dynamic as the progression of realism.

The progression of realism means above all a continual renewal of the value of computer graphics by injecting new effects into the market. Specific effects to develop in order to achieve better realism are suggested in "The Progression of Realism," such as the "complexity" of geometry and surfaces, and the accurate simulation of material properties and lighting. However, as I have tried to show, the computer graphics literature is not characterized by an unbroken and centrifugal development, and instead reveals oblique, *historical* uses of methods of simulation that we call realistic. The global market has been a transforming condition for computer graphics since the 70s, built alongside the production of computer graphics knowledge and modulating it in profound ways. The huge value-producing apparatus that uses computer graphics consists not just of academic scientific research into graphics and a computer graphics industry, but also of a productive culture of realism that secretes onto itself images about the real.[68] Consider that through the progression of realism, computer graphics functions as a form of mechanical reproduction satisfying "the desire of contemporary masses to bring things 'closer' spatially and humanly."[69] Computer graphics as realistic simulation is a major capability of our world for reproducing everything that is unique and inaccessible for a global market that demands access to everything, and it mediates the exchange relation through the commodification of reality. But in order to do this it requires the renewal of the value of the real just as it claims to simulate the real. By attending to the transitional period of computer graphics knowledge in the 60s,[70] I hope that we can denaturalize our ideas about computational media, see what produces its use, and build alternatives.

Notes

[1] For a recent summary of these positions see Gaboury, Jacob. *Image Objects: An Archaeology of 3D Computer Graphics, 1965-1979.* New York University, 2014, pp. 41-44. *ProQuest*, Order No. 3643021.

[2] Manovich, Lev. *The Language of New Media*. The MIT Press, 2001, pp. 94-111. For a discussion of the computer as a metamedium see Manovich, Lev. *Software Takes Command*. Bloomsbury Academic, 2013.

[3] In part I take after Jameson, Frederic. *Postmodernism, or, The Cultural Logic of Late Capitalism*. Duke University Press, 1991.

[4] My research is inspired of course by Foucault's project of archaeology, and also by Jonathan Crary's analyses of the transformation of knowledge in the 19th century. See Foucault, Michel. *The Archaeology of Knowledge*. Vintage Books, 2010. See also Crary, Jonathan. *Techniques of the Observer: On Vision and Modernity in the Nineteenth Century*. The MIT Press, 1990. and Crary, Jonathan. *Suspensions of Perception: Attention, Spectacle, and Modern Culture*. The MIT Press, 1999.

[5] I follow Jacob Gaboury and James Lehning for most of the section on the initial history of the University of Utah and Evans & Sutherland in the mid-to-late 60s. See Gaboury, Jacob. "Other Places of Invention: Computer Graphics at the University of Utah." *Communities of Computing: Computer Science and Society in the ACM*, UC Berkeley, 2016, pp. 259-285. See also Lehning, James. "Technological Innovation, Commercialization, and Regional Development: Computer Graphics in Utah: 1965-1978." *Information & Culture*, vol. 51, no. 4, 2016, pp. 479-499. doi:10.7560/IC51402. For a brief overview of the University of Utah and a general history of computer graphics from the perspective of a practitioner in the field, see the sprawling Carlson, Wayne E. *Computer Graphics and Computer Animation: A Retrospective Overview*. The Ohio State University, 2017.

[6] Copies of the ARPA contract reports referenced were obtained from the digital archives of the J. Willard Marriott Library at the University of Utah.

[7] Roberts, Lawrence. *Machine Perception of Three-Dimensional Solids*. Massachusetts Institute of Technology, 1963.

[8] Sutherland, Ivan E. *Sketchpad, A Man-Machine Graphical Communication System*. Massachusetts Institute of Technology, 1963.

[9] Johnson, Timothy. *Sketchpad III, Three Dimensional Graphical Communication With a Digital Computer*. Massachusetts Institute of Technology, 1963.

[10] Licklider, J. C. R. "Man-Computer Symbiosis." *IRE Transactions on Human Factors in Electronics*, vol. HFE-1, 1960, pp. 4-11. For another example from this time also see Licklider, J. C. R. and Clark, Welden E. "On-Line Man-Computer Communication." *AIEE-IRE 1962 Proceedings*, Spring, 1962, pp. 113-128.

[11] Sutherland, Ivan E. "The Ultimate Display." *Proceedings of IFIP Congress*, 1965, p. 506.

[12] Johnson, p. 16.

[13] For an account of perspective from antiquity to the Renaissance see Panofsky, Erwin. *Perspective as Symbolic Form*. Translated by Christopher S. Wood, Zone Books, 1997. For an interesting critique of Panofsky's notion of perspective as the reflection of a dominating cultural form also see Scolari, Massimo. *Oblique Drawing: A History of Anti-Perspective*. The MIT Press, 2012. Note Scolari's description of orthographic projections during the Renaissance in architecture and military engineering, contexts where the edges of a model were required to be easily measurable.

[14] For a material reading of solutions to this important early problem see Gaboury, Jacob. "Hidden Surface Problems: On The Digital Image as Material Object." *Journal of Visual Culture*, vol. 14, no. 1, 2015, pp. 40-60. doi:10.1177/1470412914562270.

[15] Roberts, p. 8.

[16] Ibid, p. 72.

[17] "Other Places of Invention: Computer Graphics at the University of Utah," p. 278.

[18] Lehning, p. 492.

[19] Evans, David C. "Graphical Man/Machine Communications: May 1969 AD700097." Advanced Research Projects Agency/University of Utah, 1969, p. 6.

[20] Lehning, p. 483.

[21] Evans, David C. "Graphical Man/Machine Communications: November 1966 AD805134." Advanced Research Projects Agency/University of Utah, 1966, p. 3.

[22] Wylie, Chris et al. "Half-Tone Perspective Drawings by Computer." *AFIPS 1967*, Fall, pp. 49-58.

[23] Ibid, p. 49.

[24] Ibid, p. 56.

[25] Ibid, p. 58.

[26] See the following: Weiss, Ruth A. "BE VISION, A Package of IBM 7090 FORTRAN Programs to Draw Orthographic Views of Combinations of Plane and Quadric Surfaces." *Journal of the Association for Computing Machinery*, vol. 31, no. 2, 1966, pp. 194-204. Appel, Arthur. "The Notion of Quantitative Invisibility and the Machine Rendering of Solids." *ACM 1967 Proceedings*, pp. 387-393. Appel, Arthur. "Some Techniques for Shading Machine Renderings of Solids." *AFIPS 1968 Proceedings*, Spring, pp. 37-45. Comba, Paul G. "A Procedure for Detecting Intersections of Three-Dimensional Objects." *Journal of the ACM*, vol. 15, no. 3, 1968, pp. 354-366. Bouknight, J. and Kelley, K. "An Algorithm for Producing Half-Tone Computer Graphics Presentations With Shadows and Movable Light Sources." *AFIPS 1970 Proceedings*, Spring, pp. 1-10. Loutrel, Philippe P. "A Solution to the Hidden-Line Problem for Computer-Drawn Polyhedra." *IEEE Transactions on Computers*, vol. 19, no. 3, 1970, pp. 205-213.

[27] "The Notion of Quantitative Invisibility and the Machine Rendering of Solids," p. 1.

[28] "Some Techniques For Shading Machine Renderings of Solids," p. 1.

[29] Cole, A. J. "Plane and Stereographic Projections of Convex Polyhedra from Minimal Information." *The Computer Journal*, vol. 9, no. 1, 1966, pp. 27-31.

[30] Evans, David C. "Graphical Man/Machine Communications: November 1968 AD847432." Advanced Research Projects Agency/University of Utah, 1968, p. 7.

[31] Warnock, John. "A Hidden Line Algorithm for Halftone Picture Representation." University of Utah, 1968.

[32] Warnock, John. "A Hidden Surface Algorithm for Computer Generated Halftone Pictures." University of Utah, 1969.

[33] "Other Places of Invention: Computer Graphics at the University of Utah," p. 281.

[34] "A Hidden Surface Algorithm for Computer Generated Halftone Pictures," p. 18.

[35] Ibid, p. 1.

[36] "Some Techniques For Shading Machine Renderings of Solids," p. 1.

[37] Roberts, p. 12.

[38] See Arnheim, Rudolf. *Film as Art*. University of California Press, 1957, pp. 8, 154-160.

[39] See the catalog of works in Hultén, Pontus K. G. *The Machine, As Seen at the End of the Mechanical Age*. The Museum of Modern Art, 1968.

[40] Watkins, Gary S. *A Real-Time Visible Surface Algorithm*. University of Utah, 1970.

[41] Evans, David C. "Graphical Man/Machine Communications: May 1971 AD725102." Advanced Research Projects Agency/University of Utah, 1971, p. 3.

[42] Evans, David C. "Graphical Man/Machine Communications: June 1971 AD738293." Advanced Research Projects Agency/University of Utah, 1971, p. 3.

[43] Gouraud, Henri. *Computer Display of Curved Surfaces*. University of Utah, 1971.

[44] Ibid, p. 1.

[45] Evans, David C. "Graphical Man/Machine Communications: June 1972 AD754282." Advanced Research Projects Agency/University of Utah, 1972, p. 4.

[46] Gouraud, p. 32.

[47] Evans, David C. "Graphical Man/Machine Communications: December 1971 AD748240." Advanced Research Projects Agency/University of Utah, 1971, p. 11.

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[52] Newell, Martin E. et al. "A Solution to the Hidden Surface Problem." *ACM 1972 Proceedings*, vol. 1, pp. 443-450.

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[54] For a history of the early relationship between memory and the raster image see Gaboury, Jacob. "The Random-Access Image; Memory and the History of the Computer Screen." *Grey Room,* Winter, no. 70, 2018, pp. 24-53.

[55] "A Solution to the Hidden Surface Problem," p. 448.

[56] Blinn, James F. and Newell, Martin E. "Texture and Reflection in Computer Generated Images." *Communications of the ACM*, vol. 19, no. 10, 1976, pp. 542-547.

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[62] "Other Places of Invention: Computer Graphics at the University of Utah," p. 283

[63] Whitted, Turner. "An Improved Illumination Model for Shaded Display." *Communications of the ACM*, vol. 23, no. 6, 1980, pp. 343-349.

[64] Ibid, p. 1.

[65] Newell, Martin E. and Blinn, James F. "The Progression of Realism in Computer Generated Images." *ACM 1977 Proceedings*, pp. 444-448.

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[70] I echo here Hansen, Miriam. "Early Cinema, Late Cinema: Permutations of the Public Sphere." *Screen*, vol. 34, no. 3, 1993, pp. 197-210. See also Gunning, Tom. "An Aesthetic of Astonishment: Early Film and the Incredulous Spectator." *Art & Text*, Spring, no. 34, 1989, pp. 31-45.