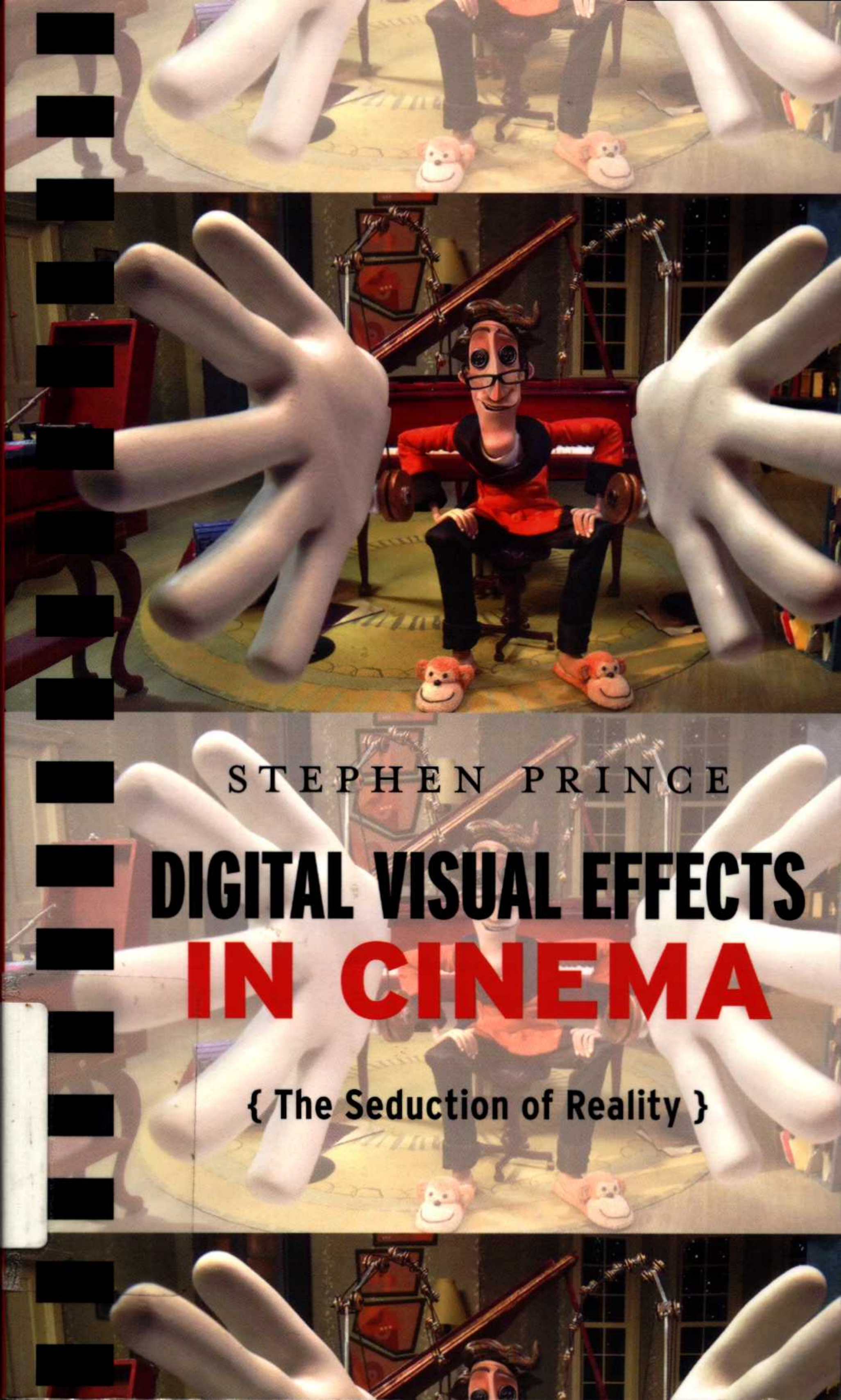

STEPHEN PRINCE

DIGITAL VISUAL EFFECTS IN CINEMA

{ The Seduction of Reality }

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CHAPTER 1

Through the Looking Glass

The digital era in cinema challenges our understanding of the medium and not simply because of the shift to electronics from celluloid. It challenges us to think anew about the nature of realism in cinema and about the conjunction between art and science, as these domains collaborate in the design and use of technologies that make possible the creation of a new class of images, ones that have a transformative effect on existing media and offer viewers opportunities to enter new optical domains. As Barbara Maria Stafford points out, visual technologies are "tools for transformation and revelation [and] expand human consciousness."[1] Digital tools are merely the latest instance in a long history of imaging technologies that have been designed to take viewers through a looking glass into domains of novel perceptual experience. As Scott Bukatman notes, "The special effects of contemporary cinema are . . . a more recent manifestation of optical, spectacular technologies that created immersive, overwhelming, and apparently immediate sensory experiences."[2] For centuries, optical technologies have offered art and science a productive meeting place, and digital applications exemplify this relationship. Digital visual effects come to us by way of the phenakistiscope. Nothing ever happens for the first time in film history, and we can learn about contemporary imaging modes by keeping in mind the bridge between art and science that gave birth to the movies. This will enable us to chart a different investigative direction into digital cinema than more familiar ones that equate visual effects with the provision of spectacle and that regard effects as being mostly incompatible with realism.

Before taking up these topics, I offer in this chapter some necessary historical and theoretical background. I begin by examining the arrival of cinema's digital era by tracing the development of computer graphics and their application to cinema, paying particular attention to the achievements

Visual effects often are equated with eye-popping spectacle, but digital tools have enlarged domains in which effects operate and have enabled filmmakers to achieve greater levels of realism in representing a world on screen. *The Mask* (1994, New Line Cinema). Frame enlargement.

in *Jurassic Park* (1993), the film that unequivocally demonstrated for Hollywood the benefits of computer-based imaging in narrative filmmaking. I then explore the union of art and science in cinema's prehistory and its relevance for understanding digital visual effects as more than spectacle. I conclude by examining the complexity of viewer response to pictorial illusion in ways that inflect the construction of visual effects.

The Development of Computer Graphics

If the 1990s were the takeoff years for digital effects in cinema (the "wonder years," in Michelle Pierson's terminology),[3] the foundations for the new generation of images appearing in *Terminator 2* (1991), *Death Becomes Her* (1992), *Jurassic Park*, and *Forrest Gump* (1994) were established in the 1960s and 1970s at a series of industry and academic research labs, including MIT, Harvard, Ohio State University, the University of Utah, Xerox Palo Alto Research Center, Bell Labs, Lawrence Livermore National Laboratory, and the New York Institute of Technology (NYIT). The period saw a burgeoning interest among academics and industry professionals in engineering, electronics, and computer science to extend the computer's capabilities, using them to draw, paint, model solid objects, and even make films.

The research generated numerous academic papers and dissertations, and in 1974 the area's professional interest group, SIGGRAPH (Special Interest Group on Computer Graphics, as it was then called), held its first conference. As many of the algorithms and procedures basic to computer imaging were developed, the available computer memory and its prohibitive cost meant that implementing these breakthroughs in a high-resolution medium like cinema remained years away. Computational power, however, was not the only constraint. The behavior of natural phenomena needed research and study from the standpoint of computer modeling. As a 1983 SIGGRAPH roundtable on the simulation of natural phenomena noted, "Most items in nature, trees, clouds, fire and comets being some examples, have not been displayed realistically in computer graphics. . . . Previous attempts at realism have dealt with the appearance of the surfaces being modeled, in terms of their illumination or relief. . . . However, it appears that natural phenomena will require more research into the fundamental way things occur in nature, and in terms of computer graphics, their representation will build on previous work, but will still require new modeling techniques."[4] Modeling reality in the computer in perceptually convincing pictorial forms proved to be quite difficult.

The high cost of computing and such "lack of understanding of the intricacies of the picture-generating software that would be needed for an effective computer graphics system" impeded progress.[5] But as the cost of memory plummeted, the introduction of powerful small computers on a workstation model made it possible to take computer graphics to high resolution and pictorially complex domains. Thus it is in the early 1980s that computer graphics and feature filmmaking begin to intersect in major and substantial ways, although Hollywood was slow to adopt digital imagery in this period. By contrast, computer-generated imagery was more plentiful on broadcast television, where it appeared in advertising and as corporate logos. Corporate advertising budgets could afford the cost-per-minute expenditures that made short CGI effects feasible; Hollywood as yet could not. Moreover, film was more unforgiving of digital artifacts than the low-resolution medium of television. Digitally animated artwork graced the opening of *Entertainment Tonight* in 1983 and ABC's Winter Olympics coverage the following year, and flying logos appeared on the nightly network newscasts and broadcasts of National Football League games.

Fully functional electronic computers date to the ENIAC (Electronic Numerical Integrator and Computer) in 1946, designed and developed by the U.S. Army during World War II for use in ballistics research. Military contracting provided a powerful incentive for the initial research on digital computing. The Whirlwind, developed for the U.S. Navy in 1951 and adopted in a later version by the Air Force in its SAGE air defense program, was the first digital computer that displayed real-time graphics on an oscilloscope screen. Data entry was interactive. Using a light pen, Air Force personnel could input instructions to the computer to track specific aircraft, making it the first interactive computer graphics system.

Although the initial developments in high-power computing occurred in a military and industrial context, the potential to use computers for aesthetic ends swiftly emerged. As programming languages such as FORTRAN (1954) and BASIC (1964) enabled computers to perform an increasing variety of tasks, artists as well as mathematicians and engineers were drawn to the idea of creating graphics via computer. Charles Csuri, a computer scientist at Ohio State University, predicted that art and science would draw closer together. "The frontiers of knowledge in computer research offer a glimpse into the future role of the artist. . . . The computer, which handles fantastic amounts of data for processing, brings the artist close to the scientist. Both can now use the same disciplines and knowledge in different ways."[6] Wayne Carlson points out that the difference in this early period between artists and scientists drawn to the computer's graphic capabilities "was blurry at best."[7] Beginning in 1950, Ben Laposky, for example, a mathematician and artist, used cathode ray oscilloscopes to create abstract visual designs he called Oscillons. Bell Labs developed a computer animation system in 1963 and used it to produce films by avant-garde filmmaker Stan VanDerBeek. John Whitney, another cinema artist, embraced digital imaging. After making a series of experimental films in the 1940s, Whitney began to build what he termed mechanical drawing machines, assembled from discarded military hardware, to create and photograph abstract patterns of motion. In 1957 he rebuilt an army surplus mechanical (nondigital) computer that had been used in an anti-aircraft gun system so that he could use it to control a camera (thus taking a major step along the path to motion-control cinematography). He used it to mechanically orbit a strip of film negative displaying the number 1961 and filmed these orbits frame by frame, graphically transforming the numbers into abstract shapes and creating streaks of colored light in a film entitled *Catalog* (1961). Saul Bass used Whitney's machine in designing the title sequence to Hitchcock's *Vertigo* (1958), which featured Oscillon-type imagery, and Whitney created titles for the *Bob Hope Television Show*, *The Dinah Shore Show* and MGM's Doris Day movie *The Glass Bottom Boat* (1966). Whitney believed that computers offered a revolution in the visual arts, the possibility of creating a "liquid architecture," one in which computer manipulation of motion patterns could enable him to find visual equivalents for the dynamic harmonic structures of music. He wrote about this objective in his book *Digital Harmony*, where he observed that the graphic domain enabled by computers would be of historic proportions. "Before us lies an optical domain which may prove to be quite as vast as the historic world of music."[8]

Michael Noll, who created digital art for Bell Labs in the early 1960s, published a paper in 1967 boldly entitled "The Digital Computer as a Creative Medium" in which he observed, "Composers, film animators, and graphic artists have become interested in the application of computers in their creative endeavors."[9] "This is not to say that the traditional artistic media will be swept away," he predicted, quite presciently, "but they will undoubtedly be influenced by this new active medium. The introduction of photography—the new medium of the last century—helped to drive painting away from representation, but it did not drive out painting. What the new creative computer medium will do to all of the art forms—painting, writing, dance, music, movies—should be exciting to observe."[10]

Computer graphics began with the work of Ivan Sutherland, a doctoral student at MIT, who, for his dissertation, created in 1963 a program and associated hardware called Sketchpad. It employed a graphical user interface (GUI) and a light pen to enable simple line drawing on a cathode ray tube. In his 1963 paper "Sketchpad: A Man-Machine Graphical Communication System," Sutherland wrote, "The Sketchpad system makes it possible for a man and a computer to converse rapidly through the medium of line drawings. Heretofore, most interaction between man and computers has been slowed down by the need to reduce all communication to written statements that can be typed. . . . The Sketchpad system, by eliminating typed statements (except for legends) in favor of line drawings, opens up a new area of man-machine communication."[11]

Sketchpad treated pictures as a nested hierarchy of structures, enabling the user to manipulate portions of an image, including such now-standard commands as copying, moving, resizing, rotating, and zooming. Intended as a tool for creating engineering drawings (and thus a predecessor of CAD/CAM or computer-assisted-design/manufacturing systems, the first of which, DAC-1, debuted in 1964 as a joint effort of General Motors and IBM), it employed vector graphics, a system for creating geometrical forms by storing the information about them as mathematical formulae, a method compatible with the restricted memory capabilities of the period. Vector systems draw simple lines rather than carrying out complex operations directly on pixels (the smallest picture unit of a digital image or display), as do raster displays. Sutherland aimed to move toward a raster-based graphics system where pictorial manipulations could be performed on pixels themselves. (Raster scanning was the technology employed on standard television CRTs. The barrier it presented to computer imaging was the memory necessary for storing an entire screen's worth of pixel information.) In 1968 he joined David Evans at the University of Utah, where they formed a computer graphics department sustained by a $5 million grant from the Department of Defense's Advanced Research Projects Agency (ARPA). ARPA wanted them to develop a flight simulator for pilot training, but this required raster graphics in order to represent landscape surfaces. The primitive lines supplied by vector graphics were insufficient for displaying the tonal and textural detail needed for landscape representation. A raster system required both enough memory (what soon would be called a frame buffer) to store the pixel information and also programs for manipulating it, which didn't yet exist. Research at Utah, therefore, went into working toward raster graphics with a usable frame buffer and into creating, modeling, and lighting 3D objects in computer space. By the end of the 1960s, it was possible to build wireframe models in the computer and subject them to transformations and rotations. Subsequent research in the 1970s went toward developing the surface-level algorithms necessary for representing textures, tones, shadows, and highlights.

With Evans, Sutherland also formed the company Evans & Sutherland (E&S), which contracted with the Defense Department to build computer simulators for airplanes and ships. By 1974 E&S was marketing a commercial frame buffer following the development in 1972 by Xerox researcher Richard Shoup of a system he called "picture memory," an early iteration of frame buffering. Initial computer paint systems also developed in this period, enabling artists to work directly on pixels. At Xerox, Shoup created "Superpaint," the first 8-bit paint system.[12] Digital images derive from pixels, and each pixel has three components or channels—red, green, blue—determining color intensity. Bit depth measures the amount of color resolution contained in a computer image according to the number of bits assigned to each component. (A bit comprises the binary distinction 0 or 1.) An 8-bit system can display 256 colors.

Breakthroughs at MIT in the 1960s included Steven Coons's work on "surface patches," a formulation for representing curved surfaces as found on the hull of a ship or fuselage of an airplane. Curves were a problem for wireframe models of objects because these were built in the computer using polygons, simple, closed plane shapes that had hard edges and vertices. Polygons were not very accurate in representing curved surfaces. Coons's formulation of surface patches enabled the representation of more complex shapes than polygons afforded, and he envisioned his mathematical formulae as a means for enhancing the artistic potential of computer design by removing "almost entirely the need for the designer to be an analytic geometer." The computer would assume the geometric calculations and number crunching "and leave the user free to be a sculptor assisted by an exquisitely skillful mechanical slave."[13] Lawrence Roberts solved a critical issue in the machine replication of 3D visual data by creating an algorithm for hiding the occluded surfaces in computer-built objects. His program enabled a computer to "process a photograph into a line drawing, transform the line drawing into a three-dimensional representation and, finally, display the three-dimensional structure with all the hidden lines removed, from any point of view."[14] Thus the final 2D display would have hidden surfaces concealed from the viewer's line of sight, a necessary achievement in representing an observer's field of vision.

Developments like hiding occluded surfaces required the accumulation of complex knowledge about dimensional transformation; to appreciate this, one needs to consider the differences between painting on a 2D surface and computer modeling. The painter creates an illusion of depth, but the suggested recession of objects doesn't truly exist because the canvas is a flat surface. The painter creates an impression of 3D space, but the computer artist must create that space. The computer artist must define and then control true three-dimensional relationships and be able to translate that information accurately to the terms of a 2D viewing surface. This is no simple task, and its challenges help explain why the algorithms for a realistic representation of space in computer images were relatively slow in coming. Robert Rivlin perceptively expressed the problem this way: "For the artist, a three-dimensional object or landscape portrayed on a two-dimensional surface merely has to look real. But a model in the computer database must, for all intents and purposes, actually simulate the properties of a three-dimensional object in nature. The single view of an object in a painting or drawing is not enough for an interactive three-dimensional computer-graphics display."[15] The latter must allow for any view possible within three-dimensional space, with the appropriate transformations, such as surface occlusion relative to the viewing angle.

As these modeling achievements were occurring at Utah, MIT, Xerox, and elsewhere, entrepreneur Alexander Schure, who had financed and launched NYIT in 1955, added a Computer Graphics Laboratory to pursue applications to film. Interested in making animated movies, Shure wanted to find ways of using computers to ameliorate problems that existed in traditional cel animation, such as the labor-intensive process of animating all frames instead of simply the keyframes (with a computer handling the rest).

Schure recruited a team of computer graphics specialists, some from the program at Utah, to research methods of digital animation that could be employed to produce a feature-length film. One of the Utah graduates, Edwin Catmull, had already created a short 3D animation—*Hand* (1973)—by using his own hand as a source for 3D modeling. As noted, solid objects in computers were beset by the hard edges and sharp corners that derived from the underlying polygons used to make them, and Catmull's research extended Coons's methods for smoothing edges and surfaces. Catmull developed algorithms generating curved parallelograms assembled in patches or clusters to quickly build smooth, curved surfaces on an object, and he also helped implement the process of wrapping textures onto a geometric model (texture mapping). (Catmull's work and career exemplify the intersection of science and art manifest by the research in computer graphics. He went on to become president of Pixar Animation Studios.) The NYIT researchers examined basic problems of lighting and texturing that needed solving in order to produce real-looking images from objects modeled in the computer.

Recognizing that computer imaging needed the ability to capture translucent surfaces, Catmull and Alvy Ray Smith, another researcher at NYIT, developed the alpha channel, which specifies an object's degree of opacity. In addition to the red, blue, and green channels, the fourth, alpha, channel describes not how colorful a pixel is but how transparent it is. In 1977, Smith had designed the first 24-bit paint system, capable of generating 16 million colors. Adding a fourth component or channel raised a 24-bit image to a 32-bit image. Although this required more computing power, manipulations of opacity or translucence enabled animators to make huge strides forward in their abilities to mimic the behavior of light and its interactions with solid, gaseous, and liquid objects. The alpha channel, for example, helped make possible the convincing interactions of actress Mary Elizabeth Mastrantonio with the liquid pseudopod in *The Abyss* (1989), especially during that moment when her character pokes the liquid creature with a finger. Made of seawater, the pseudopod is translucent, and the viewer sees the character's finger inside the creature, whose pixels have been rendered as semitransparent. Beyond giving computer graphics a stronger perceptual anchoring in the physical behavior of light, the alpha channel gave filmmakers another benefit. It provided an effective mechanism for matte extraction since it can be used to generate high-contrast images. Matte extraction has been an essential element of optical (and now digital) compositing throughout the history of cinema, and the alpha channel provided a new tool to augment existing means of pulling mattes.

Computer Graphics Meets Hollywood

At mid-decade the research developing around computer animation intersected with feature filmmaking. Working at the graphics company Triple-I (Information International, Inc.), John Whitney Jr. created 2D graphics for *Westworld* (1973) in scenes representing an android's electronic viewpoint. In *Future World* (1976), Triple-I created footage of a digitized Peter Fonda along with footage of Edwin Catmull's hand from his student film. The footage appeared on a monitor in the background of a shot. These debuts did not jolt Hollywood. Few even seemed to notice. But two powerful Hollywood figures—George Lucas and Francis Coppola—had a keen interest in using digital tools to simplify the labor and extend the creative possibilities of filmmaking, and, as Mark Rubin shows in *Droidmaker*, his history of Lucas's role in digitizing Hollywood, they pursued their interests in ways that altered the industry. Coppola's visions were grander and more epic than Lucas's, but his methods also were more scattershot and left less of a legacy. Lucas funded the systematic research that led to the eye-popping CGI with which he became forever after associated, an ironic outcome given his original intentions. Instead of funding research with its delayed gratifications, Coppola wanted to explore immediate applications of video and computers to filmmaking. He edited *Apocalypse Now* (1979) on videotape, for example, but then found he had no reliable way of translating his edits to film because of the different frame rates that operated in each medium. Lucas was uninterested in digital tools as a means to create special effects; he wanted to streamline film editing by removing the tedium of recording and tracking edge numbers in order to find shots. A computer could keep track of edge numbers more efficiently, and the random access permitted by a nonlinear system could speed the process of finding shots in the mass of footage. Coppola's approach was freewheeling. While it generated useful tools, such as the process of video assist that he used on *One from the Heart* (1982), it didn't have the lasting power that an institutional presence can achieve. Lucas, by contrast, had a company, and he was willing to fund a program of pure research focusing on digital applications in film production. He recruited Edwin Catmull from NYIT in 1978 to start a computer graphics program at Lucasfilm, which eventually grew into the company's Computer Development Division, which, years later, became Pixar.

Lucas had three objectives in funding the research. These were to develop a nonlinear editing system, a complementary system for digitally processing and mixing sound, and a digital film printer to replace existing optical printers. There was no point in developing computer graphics for film unless the results could be scanned onto film for exhibition. This was the objective that a digital film printer would achieve.

Lucas's pursuit of nonlinear editing eventually yielded the EditDroid at mid-decade, a random access (but analog, not digital) method using laserdiscs as the storage medium for raw footage. It was similar to the CMX 600, which had been marketed in the early 1970s to broadcasters, employing a computer interface and stacks of videodiscs containing dubs of videotape. CBS used a CMX in 1971 to edit a made-for-television movie. But EditDroid never had a commercial future because by 1988 Avid and EMC2 digital nonlinear editing systems came on the market, followed by Lightworks. In 1991 Adobe released its Premiere digital editor to the consumer market. In just a few more years digital editing held a significant and established place in Hollywood's post-production processes, making editing the first domain to go digital and be accepted by the industry as a professional standard.

Lucasfilm had a working ASP (Audio Signal Processor) by 1982, and although film sound remained analog until 1990 (when *Dick Tracy* became the first film released with a digital soundtrack), Lucasfilm used the ASP to create multichannel effects for *Return of the Jedi* (1983) and to mix sound digitally. The digital film printer and its associated computer and graphics projects evolved into Pixar (a name coined as a sexy version of pixel). Pixar officials wanted to pursue animated films, but Lucas did not. As their creative interests diverged, the companies parted ways, with Lucasfilm selling Pixar to Steve Jobs for $5 million in 1986. The chief graphics personnel left Lucasfilm to go with the new company, where they pioneered digitally animated feature films beginning with *Toy Story* (1995). But Pixar's first animated short, *The Adventures of Andre and Wally B* (1984), was made at Lucasfilm. It premiered at that year's SIGGRAPH conference and was notable for containing a convincing rendition of motion blur, an element of photorealism that digital animators had long sought. Shortly after the break with Lucasfilm, Pixar released a software package that became widely used throughout the computer graphics industry. RenderMan performed a comprehensive set of calculations that were needed in rendering—lighting, texturing, and adding other 3D effects—to wireframe models. The software calculated the physical properties of the digital set, its distances and layout, the positioning of digital characters, and the virtual camera along with its focal length, and then added appropriate lighting effects and shadows. RenderMan helped create the shimmery T-1000 robot in *Terminator 2*, penguins in *Batman Returns* (1992), the ballroom in *Beauty and the Beast* (1991), and dinosaurs in *Jurassic Park*.[16]

For his part, after the break with Pixar, Lucas continued to push the digital boundaries of cinema by shooting the next set of *Star Wars* movies on high definition video. *The Phantom Menace* (1999) was shot partly on film because high-speed HD video needed for effects work wasn't yet viable.[17] Lucas persuaded Sony to build a customized hi-def camera for his needs, and, using the Sony HDW-F900, Lucas shot all of episode two in the second trilogy, *Attack of the Clones* (2002), in digital format. He used an improved version of Sony's camera on the next installment, *Revenge of the Sith* (2005). Panavision introduced its own digital camera in 2004, the Genesis, capable of accommodating Panavision's standard line of 35mm film lenses. *Superman Returns* (2006), *Flyboys* (2006), *Apocalypto* (2006), and many other films have been shot with the Genesis. Lucas did not singlehandedly move feature cinematography into a digital realm, however. Cinematographer John Bailey had already shot *The Anniversary Party* (2001) on digital video, and methods of digitally grading film images to adjust color and other tonal values were employed on *Pleasantville* (1998) and *O Brother, Where Art Thou?* (2000). But Lucas and his company were the powerhouse, and his efforts in taking cinematography in a digital direction helped to establish digital image capture as a professional industry standard. Other major filmmakers swiftly identified themselves with digital image capture. Prominent among these have been David Fincher (*Zodiac*, *The Curious Case of Benjamin Button*) and Michael Mann (*Collateral*, *Public Enemies*).

Although digital effects were not part of George Lucas's original vision, the effects created by the artists at ILM became widely identified with the filmmaker and his company as its primary product and influence on cinema at large. In light of this popular legacy, interestingly, Lucas was relatively slow to incorporate digital effects into his own films. *Star Wars* (1977) included a brief 3D computer graphic visualizing the planned attack on the Death Star. (Other computer screens in the film displaying graphics were animated by hand. The innovative computer work on *Star Wars* lay not in digital effects but in motion-control cinematography. A computer-controlled camera made multiple, exactly repeatable passes, photographing a model numerous times to create the layers of elements needed for an effects shot.) On *The Empire Strikes Back* (1980), ILM explored a relationship with competitor Triple-I under which the latter was to furnish a 3D computer animation of an X-wing fighter. But ILM demurred, the effects shot was never used, and the film contained no computer graphics. The sequel, *Return of the Jedi*, used only a small amount of digital animation to simulate graphics displays. By contrast, during this period the major digital effects showcases were in films made by other production companies, some of which ILM worked on as a contractor. Chief among these was Paramount Pictures' *Star Trek II: The Wrath of Khan* (1982), whose "Genesis sequence" was the era's great industry eye-opener, showing what digital imaging could do for cinema. It contained the first application in a theatrical film of a digital paint system, a newly created 32-bit (four channel) program.[18] In the sixty-second sequence, a Genesis probe missile fired at a dead planet revivifies it. A wave of fire sweeps across the planet, leading to a lush rebirthing process on a global scale. Previous instances of digital graphics, as used in *Star Wars*, *Future World*, or 1981's *Looker*, did not aim to simulate a photographic or an organic reality. They looked like what they were—schematic computer images—and functioned in the scenes as what they were—primitive images displayed on computer monitors that the characters in the scene were viewing. (The Genesis sequence is also viewed by characters in the scene on a monitor, but it does not resemble primitive vector graphics.)

The Genesis sequence is cinema's first attempt to simulate properties of organic matter in a photographically convincing manner, one not intended to look like a computer graphic, as did the applications in earlier films. The sequence broke ground by using two relatively new modeling procedures—particle systems and fractal geometry. The sequence included such difficult-to-animate objects as fire, sparks, smoke, and clouds, and these were treated as particle systems, dynamic aggregates manifesting their own behavioral laws, spawning (or spreading in the case of fire) at a known rate and subject to the influence of wind and gravity. This was a different approach than the standard used to animate solid objects, which involved building polygon models and then texturing them. William Reeves, the Lucasfilm animator who created the wave of fire, explained the concept of particle systems in a paper prepared for the Association of Computing Machinery. He noted that "fuzzy" objects—clouds, smoke, water, fire—had proven difficult to model using existing techniques. "These 'fuzzy' objects do not have smooth, well-defined, and shiny surfaces; instead their surfaces are irregular, complex, and ill defined. We are interested in their dynamic and fluid changes in shape and appearance."[19] The method did not use fixed surface elements to define objects but rather clouds of particles, a particle being simply a point in three-dimensional computer space that changes over time in its size, coloring, and transparency. The particle system is fluid, not static, with new particles born and old ones dying. The laws governing an object's shape and behavior are not fixed and deterministic. They are stochastic, that is, a degree of randomness is included. This gives the particle system the appearance of being alive, dynamic. Treating the particles as point light sources enabled elaborate painting effects. "When many particles covered a pixel, as was the case near the center and base of each explosion, the red component was quickly clamped at full intensity and the green component increased to a point where the resulting color was orange and even yellow. Thus, the heart of the explosion had a hot yellow-orange glow which faded off to shades of red elsewhere. . . . The rate at which a particle's color changed simulated the cooling of a glowing piece of some hypothetical material."[20]

In addition to fire, the sequence also displayed convincing representations of the organic features of the Genesis planet, such as forests and mountains. These were built as fractals using stochastic processes, drawing on the skills of Loren Carpenter, a member of Lucasfilm's computer group working on the sequence but formerly a Boeing employee who had used computers to make aircraft drawings and graphics for flight simulators. Lucasfilm hired him after he presented an animated film using fractal modeling at the 1980 SIGGRAPH Conference. Entitled *Vol Libre*, Carpenter's film showed traveling aerial views of mountains and valleys, with appropriately scaled object resolutions changing according to camera distance. As Carpenter wrote in his SIGGRAPH paper, "Fractals are a class of highly irregular shapes that have myriad counterparts in the real world, such as islands, river networks, turbulence, and snowflakes."[21] He noted that fractal sets are self-similar. "Self-similarity refers to the property of a form that remains unaltered through changes in scale."Because each part of a fractal is structurally like the others, they can be recursively subdivided to change scale or to create new objects. Introducing a degree of randomness into the structures enables the artist to simulate an organic look by making edges and shapes appear rough and irregular. Carpenter had been inspired by Benoit Mandelbrot's book *The Fractal Geometry of Nature*, in which the mathematician argued that these formulas organized many organic, natural forms. (*Cinefex* writer Joe Fordham points out that when Mandelbrot passed away, computer graphics artists mourned him as "one of their founding fathers.")[22] In another paper, Carpenter and his coauthors wrote, "The importance of the stochastic properties of the real world will lead to greatly increased flexibility in the modeling techniques used in computer graphics."[23] In *Vol Libre* he showed that fractals and stochastic modeling had a key place in computer animation. The Genesis sequence brought this application to a much wider audience than had *Vol Libre*, and it was the first stand-alone, all-digital sequence to appear in a feature film.

A few months after *The Wrath of Khan* opened, Disney released *Tron*, the second prominent industry feature to showcase computer graphics. The film portrays a computer specialist who is bodily transported into the digital world of a mainframe computer, where he has a series of adventures in a tyrannical electronic world. The cleverest sequence in the film occurs during this transporting. As Kevin Flynn (Jeff Bridges) is scanned into the computer, he is converted into a wireframe model composed of a series of polygons, reversing the sequence by which computer graphics generate solid objects that begin as polygon models. Triple-I and several other companies (not including Lucasfilm) created the digital effects, which were more plentiful than in any previous film—fifteen minutes of all-digital imagery and an additional twenty-five minutes composited with live action. Unlike the Genesis sequence in *The Wrath of Khan*, however, the effects do not emulate photorealism or an organic world. Because the narrative premise is that the hero is inside a computer, the landscapes are meant to look electronic rather than natural. The viewer is intended to see that they are not real. Thus, they lack texturing and modeled lighting and look like vector graphics, composed of hard, clear, geometrically simple lines instead of analog surfaces. This look was probably unappealing to a wide audience in comparison with the kind of photorealism that computer graphics in cinema have generally aimed to emulate. Although the film's box office performance was not poor, critical reviews were tepid and the industry perceived the film as a failure. At least, that is, initially. *Tron* gained a cult following in the decades after its release, one sufficiently devoted to the film that Disney produced a sequel, *Tron: Legacy* (2010), whose 3D digital design softened the hard and unappealing vector graphics-look of the original and used the art of motion capture that had matured during the intervening years.

Hollywood continued exploring digital effects in feature films but without the boxoffice success that could be galvanizing and industry-changing. *The Last Starfighter* (1984) featured twenty minutes of CGI, and a human being was digitally animated for a brief effect in *The Young Sherlock Holmes* (1985). The level of image control achieved in the watery pseudopod crossed thresholds in digital animation, but *The Abyss* performed poorly at the domestic box office. Digital effects remained expensive, and no film had yet demonstrated conclusively that the artistic results of such expense could in themselves command wide popular appeal.

Spielberg's Dinosaurs

Terminator 2 was the first blockbuster to carry extensive digital effects. Its global box office was just over $500 million, and in its wake numerous films began utilizing computer graphics. Sometimes this was for showy ends, as in the outré contortions (a turned-around head, a giant hole in the chest) visited upon Meryl Streep's character in *Death Becomes Her* (1992), but in other cases, such as the Clint Eastwood thriller *In the Line of Fire* (1993), crowd-augmentation effects were unobtrusive and dramatically realistic. While the early 1990s saw an uptick in the use of computer graphics in feature films,

Terminator 2 (1991, Carolco Pictures) was the first blockbuster to feature extensive digital effects, but it was Steven Spielberg's *Jurassic Park* (1993) that galvanized the industry. Frame enlargement.

it was *Jurassic Park* in 1993 that demonstrated their dramatic and economic potential more vividly than any previous film. It met with a smashing box office reception. The film's global gross was nearly $1 billion. Partly this was attributable to the enduring popularity of dinosaurs, which have a long history in fantasy films, going back at least to Willis O'Brien's work on *The Lost World* (1925), where stop-motion animation brought miniature puppets to life. With his unerring commercial instincts, Steven Spielberg tapped into this enduring fascination.

But the film's digital aura also worked in its favor. A carefully orchestrated marketing campaign promoted the film's use of digital images and promised viewers they would see dinosaurs that were more vivid and lifelike than any they had seen before in the movies. This aura was enticing, alluring—it promised viewers a radically new experience, and dinosaurs were the perfect vehicle for launching an era of unprecedentedly vivid visual effects. Such promises, of course, can backfire if a film does not follow through. But *Jurassic Park* did honor its claim to give audiences a radically new experience. Its dinosaurs were remarkably vivid, and if the storyline in the film seemed a bit mechanical and the characters relatively lacking in psychological depth, the main objective held just fine, which was to engineer a series of narrative situations that would place the characters in jeopardy from prehistoric beasts. Movies like this tend to be about one thing—run from the dinosaurs!—and *Jurassic Park* contained enough such scenes to adequately deliver its goods.

Its mix of visual effects technologies made *Jurassic Park* a perfect film to usher in a new era of electronic imaging capabilities. It is an appropriately transitional film because it mixes old and new in expert and exhilarating ways. Although it is now and forever branded as a CGI film, there are only about fifty computer graphics shots in the movie. Critics and scholars tend to describe the film as if every dinosaur seen on screen came out of a computer, but most scenes involving dinosaurs feature a blend of traditional effects elements and digital ones. In this respect, the film runs counter to claims that digital technology will drive out more traditional effects tools. Voicing anxieties in the film industry that were prevalent in the period of the early 2000s, Michelle Pierson wrote that "the techniques of visual effects animation are being lost to CGI."[24] She continued, "The concern for many people trained in the techniques of makeup and prosthetics, model making, and animatronics was that the demand for this type of workmanship would simply disappear altogether should CGI ever prove capable of stimulating the materiality of physical effects effectively enough to meet with audiences' approval."[25]

To date, this kind of wholesale change has not occurred. CGI happily coexists with the traditional techniques of cinema—models, stop motion, animatronics, location filming—as *Coraline* (2009),*The Lord of the Rings* trilogy, and *Inception* (2010) demonstrate. Designing *Inception*, director Christopher Nolan stressed the value of on-location filming and practical effects accomplished in-camera and with physical sets and props. These were extended with digital tools. Real locations with actors Leonardo DiCaprio and Ellen Page included Paris streets, which were then treated digitally for a spectacular scene in which the urban environment folds up into a cube containing the actors. Nolan wanted to achieve a tactile realism and felt that only by blending physical stunts and effects with digital ones could he attain this objective.[26] Tangible benefits derive from staging things in-camera and enabling the actors to perform on location or to interact with a puppet. The emotional connection in *E.T.: The Extra-Terrestrial* (1982) between the children Elliott (Henry Thomas) and Gertie (Drew Barrymore) and their diminutive alien visitor was enriched by having the puppet on set where the child actors could interact with it. *Cinefex* writer Fordham points to another example: "I think Teddy in *A.I. Artificial Intelligence* (2001) is a more recent candidate to prove that there is still a place for practical puppets on a movie set. They made a couple of full CG versions for wide ambulatory shots, but he was brilliantly and perfectly realized by the Stan Winston team, and I would not conceive of him being done any other way today—he was supposed to be a ratty-looking but super-sophisticated mechanical bear, and I think it would have just felt wrong if he'd been done entirely as CG."[27] Despite the hype generated by *Jurassic Park*'s digital dinosaurs, they share time with animatronic models. Indeed, a significant measure of the film's artistry is its canny and often imperceptible blend of diverse effects technologies.[28] Only two scenes in the film feature all-digital

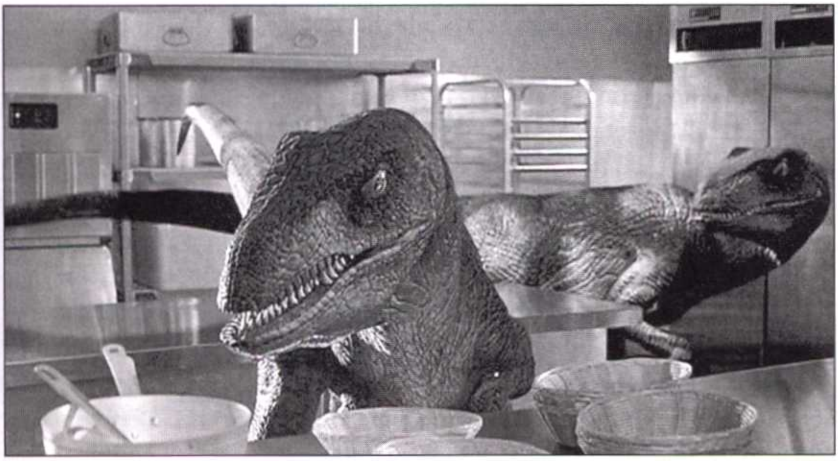
Digital tools have not replaced physical props and models in the creation of effects images. Christopher Nolan used digital tools as extensions of real locations and physical stunts throughout *Inception* (2010, Warner Bros.). Frame enlargement.

work—when paleontologists Alan Grant (Sam Neill) and Ellie Sattler (Laura Dern) see a brachiosaurus in the film's first sequence showing dinosaurs and a subsequent scene later in the film when a stampeding herd of gallimimus surrounds Grant and the children, Tim (Joseph Mazzello) and Lex (Ariana Richards). That scene ends with the giant T-Rex gobbling up a gallimimus. An extended sequence of digital animation comes at the end of the film when the T-Rex attacks two velociraptors in the park's Visitor's Center, but it is preceded by shots of the raptors menacing Grant, Sattler, and the kids that are done with animatronic models. Every other dinosaur scene in the film is done either with animatronics only or as a blend of shots featuring animatronics and CGI.

Spielberg originally planned for the film to be done with full-size robotic dinosaurs and stop-motion puppets, but this proved unfeasible. He then envisioned a blend of animatronic models designed by the Stan Winston Studio and Go-Motion puppetry designed by Phil Tippett. Animatronic models are built with motors and cables and pulleys so they can simulate character behavior. One of the most striking of these models is the ailing triceratops that Grant and Sattler find lying on its side. The model was twenty-five feet long and constructed of plywood, covered with clay and foam latex skin modeled to simulate the detailing and texturing of actual triceratops skin. The model was built with eyes that blinked, a jaw and tongue that moved, and an expandable rib cage to simulate breathing. The artistry is extraordinary, and the illusion that it creates of an ailing triceratops is overwhelmingly persuasive, so much so that many of the film's viewers may have believed it to be a digital effect. By contrast, the animatronic T-Rex was modeled in sections—separate models for a head and for legs to be used in shots featuring partial views of the creature. A huge twenty-foot-tall model was constructed for a few shots used in a nighttime attack sequence.

For a long while, Phil Tippett and other animators at ILM had been experimenting with methods of introducing motion blur into stop-motion puppetry. These methods eventually earned the name Go-Motion. Motion blur is an artifact of the camera's way of seeing. Motion pictures capture a moving subject as a series of still frame photographs, each of which freezes the action, blurring the image to a degree that depends on the camera's shutter speed. As used in films like *King Kong* (1933), stop-motion animation lacked motion blur because puppets were filmed in stationary positions, then reanimated and filmed again in a stationary position. The absence of motion blur was a giveaway that the animated puppets and the live actors in a composited shot had not been filmed at the same time or inhabited the same space. ILM's interest in correcting this facet of stop-motion animation was sustained and intense. On *Star Wars*, computer-driven motion control cameras executed moves around stationary models of spaceships and filmed them a frame at a time, capturing motion blur because the camera was moving when its shutter was open. On *The Empire Strikes Back*, the wooly tauntans were filmed as miniature puppets that were moved slightly during stop-frame filming to produce a simulation of motion blur. Phil Tippett worked on these scenes and also on those in *Dragonslayer* (1981), where a more elaborate, computer-controlled mechanism was used to move the puppet during filming. Spielberg had planned to use Go-Motion puppetry for *Jurassic Park*, but ILM, which had been retained by the production to create and animate the gallimimus sequence, ran tests indicating that digital motion blur could be effectively applied to standard stop-motion animation; further tests suggested that a full-scale CG dinosaur could be built in the computer with the requisite personality and behavioral nuances to give a compelling performance. (Fordham points out that Tippett "saw ILM's first test and said 'I am extinct.' Spielberg put the line in his film and recruited Phil to oversee the performance of CGI dinosaurs.")[29] The gallimimus sequence had been planned for digital animation because it involved aggregate herd behavior and simple crowd replication of the sort already demonstrated in other films. But a digital character, made of skin and bone and blood, giving a performance as the T-Rex and the raptors do was another thing entirely. Computers had been very good at depicting hard and/or shiny surfaces, like the T-1000 terminator or the pseudopod. An organic character performance digitally created was something new, but Spielberg was impressed with the ILM tests and boldly decided to dispense with plans for Go-Motion and instead do everything with Stan Winston's models and ILM's computer graphics. Tippett remained on the production to oversee the animated performances of the CG dinosaurs. His animators used a digital input device that translated hand-animated puppet moves to a computer model that would be used for a CG creature. The digital input device (or "dino-input-device") was a robust way of connecting traditional effects techniques with CGI. Anything that could not be done live on the set using the animatronics would be done digitally. In practice, this often meant that elaborate, complicated, or fast full-body dinosaur movements would be digital, while the models would be used for partial views of a creature, as when the T-Rex head comes into frame or the raptor feet come down in close-up on the park's kitchen floor.

The film's blending of these methods is extraordinary and subtle, even across back-to-back shots that switch from a sculpted model to a digital creature. The T-Rex attack on two park vehicles is one of the film's major set-pieces, and Spielberg films much of the action from the viewpoint of characters trapped in the vehicles as the monster threatens them. The T-Rex appears first as a Stan Winston animatronic, a partial body model. The head rises into view above the foliage surrounding the park's electrified fence. Then it vanishes back into the jungle, and when the T-Rex next appears, it does so as a digital creature seen full body, breaking through the fence and striding between the two vehicles. Spielberg cuts to a close-up of Grant and Ian Malcolm (Jeff Goldblum) in one vehicle looking off-frame, then cuts to another view inside the vehicle as the digital T-Rex stalks past the front of the



The dinosaurs in *Jurassic Park* (1993, Universal Pictures) are a brilliant blend of animatronic models and digital animation. Frame enlargement.

car, moving in a serpentine manner from head to tail. When it next appears, we again see it outside the windows of Grant and Malcolm's vehicle, but this time in a single shot that blends an animatronic model and a digital rendition of the character. Its head looms into view—the animatronic model—and as its attention is drawn to a flashlight in the other, distant vehicle, Spielberg moves the camera closer to the windshield.

The camera move accomplishes two things. It draws our attention to the flashlight in the distant vehicle where Lex in a panic has turned it on, and it causes the animatronic to move off-frame, making possible the switch. After a beat, the digital dinosaur stalks into frame as a full-body creature and moves toward the other vehicle. Spielberg cuts to Lex in terror holding her flashlight and then to a low-angle framing of her as the animatronic T-Rex head looms outside her car. In the space of three shots, Spielberg has introduced an animatronic model, then gone to a digital version of the creature, and then returned to the animatronic. Later in the sequence, Malcolm distracts the T-Rex with a flare, and as Spielberg tracks backward, Malcolm runs toward the moving camera with an enraged digital dinosaur thundering after him. Spielberg cuts to a park employee, Martin (Donald Gennaro), who has taken refuge from the attack in a restroom. A reverse-angle cut shows the animatronic head bursting into the restroom, and then a wider framing shows Martin seated on a toilet with the full-body digital T-Rex snarling at him. As this shot continues without a cutaway, the T-Rex snatches him off the toilet and gobbles him up. The action doesn't just blend live action and digital, as did the earlier shot where Spielberg switches from an animatronic model to a digital T-Rex within the same frame. They connect—the digital creature "eats" the live actor. The illusion was created by painting the actor out of the frame and replacing him with a digital character as the dinosaur's jaws engulf him.

Subliminal transitions between effects modes also distinguish a subsequent scene where two raptors stalk the children in one of the park's kitchens. The complexities of operating the animatronic puppets meant that whenever the two raptors appeared together in a shot, they couldn't both be models. As Winston observed, "We were always using either one puppet and one man in a suit, or two men in suits. We never had two puppets working simultaneously. That would have been too complicated because of the number of puppeteers it took to operate them."[30] The scene begins with one raptor standing in the doorway, portrayed by a man in a raptor suit. After a cutaway to the children, a second raptor appears in the doorway and both enter the kitchen. These were digital dinosaurs, and here as elsewhere key differences in the representation enable a viewer who wishes to do so to distinguish the digital from the nondigital dinosaurs. The digital raptors, and the digital T-Rex in his shots, move more fluidly, have a more extensive bodily articulation through movement, show a more complicated repertoire of responses, and react to stimuli faster than do the animatronic puppets or the actors in monster suits. The digital dinosaurs move in full-body shots, unlike the puppets, which are glimpsed in partial views, and the staging is composed more aggressively along the Z-axis (toward or away from the camera), as when the T-Rex chases Malcolm or kills a raptor in the last scene by thrashing it toward the camera. The sequel, *The Lost World: Jurassic Park* (1997), shows greater and more aggressive interactions between humans and dinosaurs because digital tools had advanced during the intervening years along with ILM's artistry. ILM's Dennis Muran commented that the shot designs and camera movements were conservative on the first film because everyone was a little unsure about the capabilities of the technology.[31] Camera moves in the sequel were much bolder. The round-up sequence provides vivid examples, as the camera follows dino-hunters on jeeps and motorcycles riding between, under, and through the legs of giant, galloping mamenchisaurs. The digital action is far more dynamic and visceral than what could be achieved with animatronics. Action staging occurs in and through a volume of space rather than on a plane.

Perceptual Realism

The digital animals exist only in 3D computer space and not in the world that was before the camera. The puppets, by contrast, do exist in the actual space before the camera, but they do not interact as dynamically with the actors. (Nevertheless, as noted earlier, positive benefits derive from using puppets on set with actors, chief among them being actors delivering stronger performances.) Typically, when they loom above or below or behind the actors, their movements are limited and the shots are brief because the puppets are prebuilt to move along small axes. Moreover, traditional compositing of analog effects, mixing live action with matte paintings or miniature models, required the use of stationary cameras so that the implied angles of view would match on the different image layers. Digital motion control cinematography changed this. A live-action camera can be programmed to execute the same moves as the virtual camera in computer space, and even when it isn't, a motion control artist can track the camera's move in digital space in order to build and animate a matching virtual camera. As Mark Cotta Vaz notes about the analog era, "The commandment of locking down cameras for effects photography was particularly strict in filming and compositing live action and animated elements."[32] When the T-Rex bursts through the park fence or chases Malcolm, it traverses a huge volume of space. The camera stays on the animal rather than cutting away from the digital performance, and it moves with the actor and the animated dinosaur. The depiction of space, therefore, is more dynamic, volumetric, and three-dimensional than would be possible using traditional effects techniques. Warren Buckland was sufficiently impressed by this digital ability to unify the visual space of a scene that he compared it favorably as an aesthetic of realism with the classic emphasis on deep focus that André Bazin had invoked. "We can even argue that (however paradoxical it may sound) the shots showing the humans and digital dinosaurs interacting are the digital equivalent of the long takes and deep-focus shots praised by André Bazin for their spatial density and surplus of realism, in opposition to the synthetic and unrealistic effects created by editing."[33] The new capabilities offered by digital imaging challenge scholars to rethink existing theoretical distinctions. Tom Gunning has argued forcefully that we need to move beyond the familiar dichotomies of theory: "I believe we distort our experience of films if we try to assign the effect of realism—or even the sensation of physical presence—exclusively to the photographic or confine the artificial to 'special effects.'"[34] Scott Bukatman observes as well that "a too easy historicism has tended to divide cinematic representations into naturalist and antinaturalist categories."[35]

Indeed, there are very good reasons for insisting on a critical perspective that is amenable to integrating computer graphics capabilities with aesthetic properties of realism in cinema. In an earlier essay, I identified a digital basis for realism in cinema in terms of what I called "perceptual realism," which was the replication via digital means of contextual cues designating a three-dimensional world.[36] These cues include information sources about the size and positioning of objects in space, their texturing and apparent density of detail, the behavior of light as it interacts with the physical world, principles of motion and anatomy, and the physics involved in dynamic systems such as water, clouds, and fire. Digital tools give filmmakers an unprecedented ability to replicate and emphasize these cues as a means for anchoring the scene in a perceptual reality that the viewer will find credible because it follows the same observable laws of physics as the world s/he inhabits. The referential status of the representation is less important in this conception of realism. Dinosaurs are not living beings in the age of cinema. They cannot be photographed as sentient creatures. Thus their logical status in *Jurassic Park* is as objects that are referentially false. They correspond to no reality the film's viewer could inhabit. And yet as depicted in the film they are perceptually realistic. They interact in relatively convincing ways with the live actors in a space that bonds the domains of live action and digital animation, as when the T-Rex gobbles up Martin. And because they are perceptually realistic, they are able to compel belief in the fictional world of the film in ways that traditional special effects could not accomplish. The creation of perceptual realism is a major goal of visual effects artists. Visual effects seek to persuade viewers that the effects are real within the referential terms of the story. Therefore, the more comprehensive a scene in evoking perceptual realism, the likelier it is to compel the spectator's belief. No one watching *Jurassic Park* was fooled into thinking that dinosaurs were actually alive, but because digital tools established perceptual realism with new levels of sensory detail, viewers could be sensually persuaded to believe in the fiction and to participate in the pleasures it offered. Had the film employed only traditional effects tools, this sensory persuasion would have been far less remarkable. At the same time, much of its effectiveness derives from the canny blend of CG and physical effects. As Joe Fordham points out, "It was also quite subtle, the way Spielberg used Mike Lantieri's special effects—the [CG] bronto eats the leaves from the tree-top when we first see her; Mike did that by pulling the tree and causing it to twitch. [It was] brilliantly executed when combined with the animated creature. That's why they had the strange credits on the poster: 'full motion' dinos by Dennis Muren, 'live action' dinos by Stan Winston, 'dino supervisor' Phil Tippett, and 'special dino effects' by Mike Lantieri—it was a perfect synthesis of all four."[37]

Traditional effects tools had been more limited in their ability to create perceptual realism, and augmenting them with CGI greatly enhanced the persuasive power of effects sequences. The compositing of live action, matte paintings, and miniatures in *The Lost World* (1925), *King Kong*, *The Valley of Gwangi* (1969), and other comparable creature movies was compromised by overt matte lines between the elements and by the planar rendition of space that prevented the matted creature from interacting with the live actors. Many of the jungle scenes in *King Kong* were created as multiplane projections, combinations of miniature models and sheets of glass with matte paintings on them arrayed at varying depths in the miniature set. Actors could be inserted as rear projection elements into the set. As ingenious as this design was, it kept the dramatic elements of the scene—actors, creatures, and environment—separated from one another, with little or no interaction possible. Ray Harryhausen devised an opposite system he called Dynamation.[38] As used on such films as *The Beast from 20,000 Fathoms* (1953), it utilized a split-screen matte to rear-project live action into a scene employing stop-motion puppetry. He also seized on ingenious ways of marrying live action to stop motion, as in *Jason and the Argonauts* (1963). When Jason fights the army

King Kong (1933, RKO) featured state-of-the-art composites achieved as in-camera mattes and also via optical printing. Kong as a stop-motion puppet "looks" at the live actor who has been inserted into the scene as a miniature rear projection. Frame enlargement.

of stop-motion skeletons, his sword appears to stick into them, an illusion Harryhausen created using sheets of glass in front of the puppet onto which the spear or sword emerging from its body could be painted. And yet because the stop-motion figures do not have motion blur while the live actors do, the perceptual realism of the sequence is diminished. The composited elements exhibit a perceptual disparity—limited interaction between the domains, contradictory manifestations of motion blur—working against the emergence of an organic unity of action. Under these terms, the dramatic space of the screen action becomes perceptually suspect. Digital effects promised to free cinema imagery from those problems of perceptual realism, triggering a reality-check by the moviegoer that undermined the fictional enterprise.

Perceptual realism, then, is central to understanding visual effects in cinema, the goal of effects artists, and the credibility that the effects image seeks to elicit among viewers. I have described perceptual realism in terms of the organic bonding of space between live action and digital characters as one manifestation in *Jurassic Park*. But another very significant one involves the expansion of creative possibilities for eliciting dramatic performances by digital characters. The performances by the digital dinosaurs often are more expressive than what the puppets provide. As Dennis Muran noted about the responses of the digital raptors in the kitchen scene to the sound of a falling ladle, "The foreground raptor pauses, cocks its head, then moves down quickly toward the ladle and stops absolutely on a dime. It sniffs the spoon and *quickly* jerks its head up as if it hears something. All of that action was so positive and conveyed such an attitude in the animal that it could only have been done the way we did it. The physical world would never have allowed a puppet to do that. Ten puppeteers cannot coordinate well enough to get that kind of performance."[39]

The staging of the first appearance by a dinosaur in the film is calibrated to take advantage of this potential for digitally representing performances. As park owner John Hammond (Richard Attenborough) drives Grant and Sattler through the preserve, they come upon a huge brachiosaur nibbling leaves off the tops of nearby trees. Using four moving camera shots, Spielberg provides a series of portraits of the docile, slow-moving giant as the astonished Grant and Sattler gape in awe and get out of their vehicles to walk closer. The camera movement makes the scene dynamic, but more important it connects the actors and the dinosaur, visually establishing the scene as containing a single organic space rather than different domains of live action and computer graphics. In bonding these domains, the volumetric manipulation of space in the scene is most effective and kinetic in a low-angle tracking shot that follows Grant and Sattler as they walk to a position nearly at the feet of the brachiosaur and stare upward. The extreme depth perspective in the shot vividly conveys the animal's towering size and height. In this scene as elsewhere, digital dinosaurs are rendered with finely detailed skin texture and color. The brachiosaur's skin jostles as it moves, and ILM had to figure out how to do this first-of-its-kind rendering. Muren said, "There were a lot of problems involved in creating photorealistic dinosaur skin. How do we get the light to react with it so that it has the right kind of sheen? How do we get the light to react to all the bumps on the skin? How do we create those bumps?"[40] And with the raptors and T-Rex that appeared as puppets and also in digital form, their skin had to match across their various incarnations.

The brachiosaur scene concludes with two additional shots that show a herd of the animals in the distance. All the digital shots are held leisurely on screen rather than being presented as quick glimpses. The longest lasts fourteen seconds, and this relaxed mode of presentation was essential to establishing the digital performance. Creature effects in earlier generations of film often looked quite false. King Kong is an obvious puppet, Godzilla a man in a rubber suit. To hide the fakery, filmmakers often limited the audience's views of the creature, withholding its appearance until the last moment or restricting it to a quick and fleeting appearance. Muren said, "If our sensibilities told us that we didn't want a shot to cut yet, it was great that we weren't *forced* to cut by the limitations of the technology. These shots ran and ran, giving you what your eye wanted to see, not what the filmmaker was limited to showing you."[41] This was a new kind of aesthetic freedom—the creature effects were sufficiently persuasive that filmmakers could hold on them in defiance of past conventions.

This new freedom to showcase imaginative effects accentuated an existing tension within cinema between narrative and spectacle. When a shot can run and run to show viewers what they "want to see," integrating such moments into a narrative framework requires care and attention on the part of filmmakers. Smart directors like Spielberg designed well-constructed narratives that offered appealing attractions in the form of visual effects. The aesthetic sensibility of the filmmaker counts for much in the area of visual effects as it does in other areas of film design. "I really believe the director is the most important factor in how effective digital effects can be," notes Fordham. "Spielberg is a great filmmaker; so is [David] Fincher. They appreciate and respect the power of the cinema image, so they wield it thoughtfully."[42] Predictably, some directors not as smart and accomplished as these have made the kinds of films that could be described as effects-driven. If digital tools enabled visual effects to become more assertive, some scholars felt that the results often challenged the primacy of narrative. Michelle Pierson wrote that the appearance of the brachiosaur in *Jurassic Park* stops the film's narrative so that the digital effects can be showcased at length. "The narrative all but comes to a halt, the music gradually builds, and shots of characters reacting to the appearance of the dinosaur with wonder and amazement are interspersed with long takes displaying the computer-generated brachiosaur center screen."[43] She argues that during the "wonder years" of the early nineties, digital effects broke the narrative action and were showcased in sequences that dwelled upon visual spectacle for its own sake. "These temporal and narrative breaks might be thought of as helping to establish the conditions under which spectators' willed immersion in the action—the preparedness to being carried along by the ride—is suspended long enough to direct their attention to a new kind of effects artifact."[44] In fact, considerable narrative development occurs during the brachiosaur scene—Hammond introduces Grant and Sattler to the preserve and its treasures, and he promises to tell them how he has created these dinosaurs. Geoff King is correct when he writes that the brachiosaur scene is not cut off from the narrative "for the precise reason that our contemplative gaze is motivated by that of the protagonists, getting their first stunned sight of the recreated dinosaurs, a moment loaded with narrative resonance."[45]

Narrative and Spectacle

Pierson's criticism points to an ongoing tension within the nature of cinema between narrative structure and visual effects. Aylish Wood has described this tension as "the great divide of spectacle versus narrative."[46] Critical discussion and popular culture often identify visual effects with genres like science fiction, fantasy, and action-adventure rather than taking effects as a broader category of images that are coextensive with many forms of narrative cinema. And within science fiction, action-adventure, or fantasy, effects are said to be ostentatious, attention-getting, and spectacular in ways that overwhelm narrative or halt it altogether. As Scott Bukatman writes, "What is evoked by special effects sequences is often a hallucinatory excess as narrative yields to kinetic spectatorial experience."[47] Annette Kuhn points out that "when such [special effects] displays become a prominent attraction in their own right, they tend to eclipse narrative, plot and character. The story becomes the display; and the display becomes the story."[48] Andrew Darley writes that spectacle is "the antithesis of narrative. Spectacle effectively halts motivated movement. In its purer state it exists for itself, consisting of images whose main drive is to dazzle and stimulate the eye (and by extension the other senses)."[49] Viva Paci also finds that "high-tech special effects films" undermine narrative. "These films rely on the foregrounding of visual pleasure and the almost physical participation of the viewer, as if he or she were in an amusement park. These films do not seek the viewers' attention through plot development; they capture their gaze through a 'shooting star' effect that grabs their attention—reaching out to them so to speak in their seats."[50]

Shilo T. McClean has examined the many ways in which digital effects serve the art of storytelling in contemporary film, and she argues that poorly motivated effects are better understood as reflecting deficiencies of storytelling than any characteristics that are inherent in the cinematic application of digital technology.[51] Aylish Wood maintains that even when digital effects emphasize spectacle, they still have a temporal component that generates elements of narrative.[52] Nevertheless, though popular cinema tells stories, it also attracts viewers based on its promise to show exciting and dramatic action. It always has done so. Douglas Fairbanks's swashbuckling epic *The Black Pirate* (1926) opens with a title card that is a veritable list of the exciting scenes to come—"Being an account of BUCCANEERS & the SPANISH MAIN, the *Jolly Roger*, GOLDEN GALLEONS, bleached skulls, BURIED TREASURE, the *Plank*, dirks & cutlasses, SCUTTLED SHIPS, *Marooning*, DESPERATE DEEDS, DESPERATE MEN, *and*—even on this dark soil—ROMANCE." The title card proclaims the list of attractions that the movie will offer to its viewers. Tom Gunning has argued that a cinema of attractions accounts for much of the medium's popular appeal, found in offering viewers startling visual displays that work independently of narrative. Gunning's work on the history of early film helped to establish the cinema of attractions as a core idea in the field. Objecting to what he described as the hegemony of narrative in the study of cinema, he argued in favor of a view "that sees cinema less as a way of telling stories than as a way of presenting a series of views to an audience, fascinating because of their illusory power."[53] Gunning claimed that this conception ruled cinema until around 1907 when narrative became more dominant. In a related essay, he developed the notion of an "aesthetic of astonishment" as the expressive outcome of the cinema of attractions. Visual tricks created by editing or in-camera mattes, shots of locomotives rushing toward the camera, and other abrupt or surprising views caused viewers to vacillate "between belief and incredulity."[54] Gunning elaborated, "Rather than being an involvement with narrative action or empathy with character psychology, the cinema of attractions solicits a highly conscious awareness of the film image engaging the viewer's curiosity. The spectator does not get lost in a fictional world and its drama, but remains aware of the act of looking. . . . Through a variety of formal means, the images of the cinema of attractions rush forward to meet their viewers."[55]

Gunning also claimed that the cinema of attractions never fully disappeared even after narrative became the dominant mode of popular cinema. In stressing that it "remains an essential part of popular filmmaking," he connected it with contemporary visual effects. "Clearly in some sense recent spectacle cinema has reaffirmed its roots in stimulus and carnival rides, in what might be called the Spielberg-Lucas-Coppola cinema of effects."[56] Not all film historians have accepted Gunning's claims. Charles Musser, for example, points out that many early programs of short films, cited by Gunning as attractions, in fact exhibit various modes of narrative sequencing and that a nonstop succession of shocks would have been difficult to produce and also bad showmanship: "Early films often elicited much more than astonishment—they mobilized the sophisticated viewing habits of spectators who already possessed a fluency in the realms of visual, literary, and theatrical culture."[57]

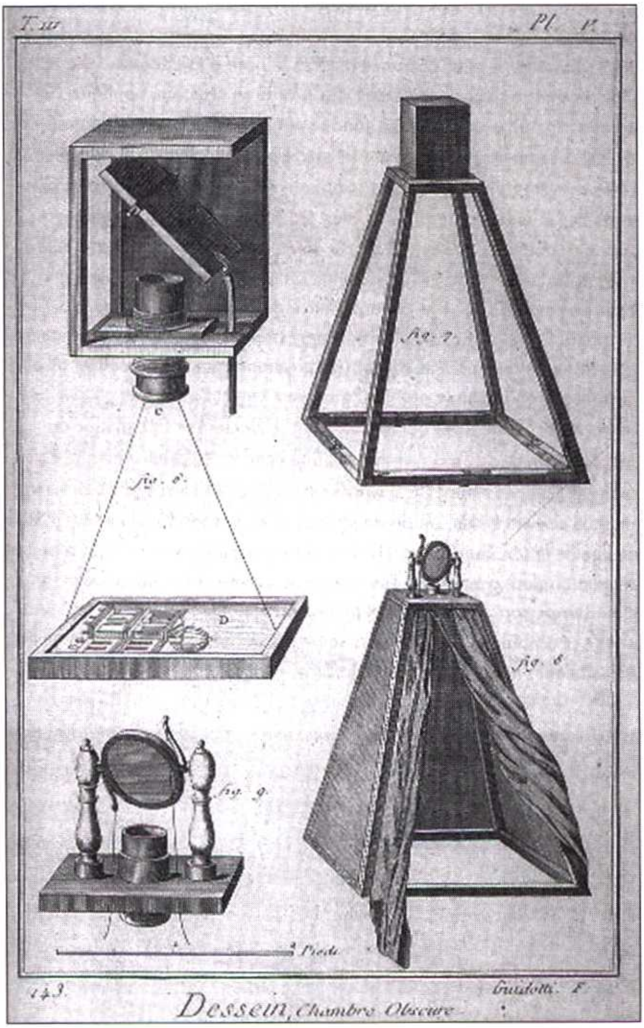
The relation between narrative and spectacle is a function of a given film's aesthetic design and the sensibilities and goals of filmmakers on a given production. Spectacle can serve narrative; it can also be a more autonomous artifact of style. There is no necessary and unchanging relation between the two. Cinema undeniably offers its viewers the pleasures that Gunning identified as those of the attraction. But it is also the case that viewers seek the pleasures offered by a well-told tale and that spectacle for its own sake, especially when poorly integrated with narrative structure or with a structure that is poorly elaborated, may be perceived as the mark of a badly made film. Viewers may nevertheless enjoy such films. Michael Bay's *Transformers* (2007) was a huge box-office hit, and, among the nearly two thousand viewer reviews on the Internet Movie Database, many say the movie was fun because the effects were great even though the script and story were perceived as poor. As Musser points out, spectators have sophisticated viewing habits, and these judgments about *Transformers* show that discriminations can be finely calibrated. In order to recognize this sophistication, we should avoid the trap that Malcolm Turvey has identified as the lure of visual skepticism. Turvey points out that "a distrust of human vision has played a foundational role in film theory." He elaborates, "It is a general, systematic doubt about normal human vision, a distrust of everyday sight. It is a belief that the standard exercise of the visual faculty is not to be trusted in some significant respect because it possesses one or more flaws."[58] The tradition of visual skepticism takes the cinema viewer as being duped by cinematic illusion and spectacle, held passively in thrall by powerful images. It can also produce other constructions of passive viewers, such as those suggesting that the experience of pictorial illusion is dependent on social conditioning and that the science and physiology of vision hold little relevance for understanding how cinema communicates and the pleasures that viewers derive from visual displays. As Jonathan Crary writes, "If it can be said there is an observer specific to the nineteenth century, or to any period, it is only as an *effect* of an irreducibly heterogeneous system of discursive, social, technological, and institutional relations. There is no observing subject prior to this continually shifting field."[59] Crary continues, "Whether perception or vision actually change is irrelevant, for they have no autonomous history. What changes are the plural forces and rules composing the field in which perception occurs." If vision is completely subordinate to social forces, then the interplay between science and cinema becomes a chimera. If vision cannot be trusted, then neither can the arts that play to its characteristics, and it becomes difficult to see viewers as being active and sophisticated. Mary Ann Doane points out that discussion of the persistence of vision in relation to cinema tends to invoke "an insistent vocabulary of deception and failure."[60]

Doane is among a group of scholars who have emphasized the connections between scientific research and the medium of cinema. Scott Curtis has written eloquently about the relationship between the modes of vision instantiated in cinematic viewing devices and in practices of medical imaging.[61] John Durham Peters has emphasized the importance of Hermann von Helmholtz's physiological studies for the history of sound film.[62] This work examines the ways that today's digital culture is, as Lauren Rabinovitz and Abraham Geil point out, a phenomenon "larger and older than the information age."[63] Indeed, cameras and other optical devices were important components used in the scientific study of vision by artists and natural philosophers and subsequently by experimental psychologists. As Lisa Cartwright notes, "Many of the techniques and instruments that contributed to the emergence of cinema were designed and used by scientists." But, she points out, in film studies, "the historical narrative quickly shifts, however, from science to popular culture."[64]

Without an emphasis upon the continuing interplay between science and popular culture, however, the operation of digital effects in cinema cannot be grasped as much beyond spectacle or attraction. Digital tools emulate properties of human vision as well as the camera's customary way of seeing things. In this regard, the application of digital tools continues a centuries-old tradition of analogizing camera and eye, and it is worth taking a moment to examine this pre-history because it provides a necessary context for understanding digital imaging tools. Visual effects belong to a long tradition of mechanically induced illusion spaces that were themselves also research tools in the development of visual science—grasping these connections and this history will enable us to move beyond the analytic template provided by notions of spectacle. In the remainder of this chapter, therefore, I recount some of this history, emphasizing the intersection of lenses, optics, and cinema with the development of scientific research into vision. In order to replicate the optical characteristics of the camera and the human eye, the digital tools used by effects artists must have an empirical grounding in this research. Digital visual effects are grounded in the science of vision at least as much as they are in the stylistics and pictorial conventions of representational images.

The Eye as an Optical Instrument

The physiologist Hermann von Helmholtz in 1868 described the eye as an optical instrument. "Regarded as an optical instrument, the eye is a camera obscura."[65] In contrast to the natural theology of the period, which extolled the perfection of human vision as an instance of divine intervention into the world, evidence of God's plan for humankind,[66] Helmholtz explicated the numerous flaws in the eye's instrumentation—chromatic and spherical aberration, lack of clarity and optical uniformity in the crystalline lens, the blind spot and other gaps in the retina. He impishly observed, "Now, it is not too much to say that if an optician wanted to sell me an instrument which had all



The first philosophical toy—the camera obscura, as diagrammed in Denis Diderot and Jean le Rond D'Alembert's *Encyclopédie* (1751).

these defects, I should think myself quite justified in blaming his carelessness in the strongest terms, and giving him back his instrument."[67] But he went on to point out that binocular vision enables each eye to compensate for the deficiencies in the other, providing a means of rectifying these flaws, and that the eye's speed was superior to that of a camera.

As Nicholas Wade and Stanley Finger write, "The overarching analogy that has been applied to the eye is that of the camera—both devices being capable of focusing on objects at variable distances."[68] The principles of the camera obscura—a dark chamber admitting a small amount of light to produce an upside down and reversed image on a flat surface of the scene or object outside the chamber (the image is upside down and reversed because the light rays cross as they pass through the hole)—were known in the eleventh century to the Islamic philosopher and scientist Ibn al-Haytham and were subsequently widely studied by artists, who used it as a device for tracing images, and by scientists seeking to understand optics and the eye. Leonardo da Vinci compared the eye with a camera obscura and experimented with the device, proposing the use of a translucent screen for tracing that would correct image reversal and eliminate the problem of the observer's head being in the path of the light. Da Vinci, though, could not reconcile the upside-down image captured by the camera obscura with the phenomenally correct perspectives supplied by human vision. The Venetian patrician Daniele Barbaro in 1568 used a convex lens and varying aperture sizes in a camera obscura to produce sharpened images on a sheet of paper.

Lenses were rapidly applied to the camera obscura, and, indeed, mirrors and lenses provided vital aids to the scientific study of vision and assisted in the development of what Martin Kemp has termed the science of art. The inventor of linear perspective, Brunelleschi, used a peephole and mirror device to heighten the illusion of depth in a painting he made of the Baptistry of Saint John. The viewer looked through a hole in a wooden panel at a mirror that reflected the image of the painting from the other side of the panel. By eliminating the problem that retinal disparity introduces into the perception of depth on a 2D surface, Brunelleschi's peepshow device heightened the illusion of depth perspective in the image. He even used burnished silver on part of the mirror to make sky and clouds more luminescent.[69] By analyzing the perspective geometry in Vermeer's paintings, Phillip Steadman demonstrated that Vermeer used a camera obscura to produce a series of portraits set in the same room of a house or studio.[70] Artist David Hockney has argued that "from the early fifteenth century many Western artists used optics—by which I mean mirrors and lenses (or a combination of the two)—to create living projections" as tools for producing paintings and drawings.[71]

The astronomers Tycho Brahe, Johannes Kepler, and Jesuit scholar Christopher Scheiner used camera obscuras to make solar observations. Kepler stated that the camera obscura provided a safe way to view a solar eclipse. Kepler proposed a system employing two convex lenses to correct the inverted image, and in 1611 he published *Dioptrice*, a seminal study of optics that emerged from his use of a telescope. ("Dioptrics" was the terminology in use for the study of refraction.) He also proposed an account of retinal vision whereby an image was focused on the retina as on a sheet of paper produced by a camera obscura and was then transmitted to the brain and its visual faculty. Scheiner produced diagrams of the eye and observed upside-down retinal images on the excised eyes of animals. He created a portable camera obscura, called the Pantograph, for making drawings of solar phenomena. Kepler, too, designed a portable camera obscura using a tent for the enclosure. The mathematician, linguist, and experimental scientist Athanasius Kircher also used a camera obscura for study of the sun, and he designed a picture-wheel projection device and a magic lantern projection system to exploit the properties of image formation in the eye that he had previously illustrated. The psychologist Nicholas Wade writes that "the photographic camera enabled artists to capture scenes in perspective with comparative ease, whereas scientists could consider the eye as a similar optical instrument."[72] Chromatic aberration in telescopes (color separation due to differences in the way a lens refracted light of varying wavelengths) and methods of correcting it helped to advance astronomy and pointed away from a corpuscular theory of light and toward a wave theory. The astronomer Christian Huygens, an early proponent of a wave theory, used the camera obscura, and Philip Steadman speculates that it was Huygens's father, Constantijn, who introduced Vermeer to optics.

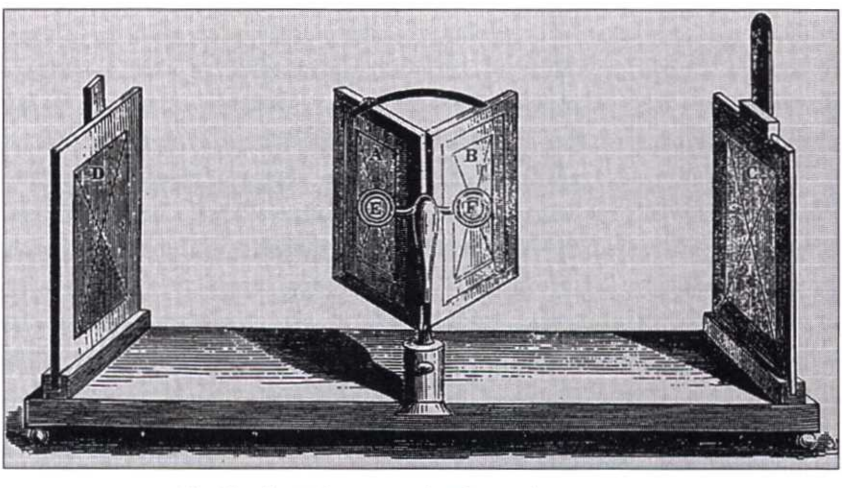
Lenses, mirrors, and the optical devices built from them provided a technical foundation upon which the study of vision could proceed, and this conjunction between image-making devices and science gives us a different inflection to cinema's historical preconditions from what prevails in the dominant, popular narrative. That narrative regards optical devices like the thaumatrope, the phenakistiscope, and the zoetrope as toys, as diversions offered to a restless public keenly interested in visual entertainments. Historian David Cook describes them as "simple optical devices used for entertainment,"[73] and Keith Griffiths writes that they helped create "phantasmagoric illusions and performances (an aesthetic of the supernatural) for the visual entertainment of the middle classes. These parlour room and entertainment hall projections helped create the public appetite for the range of entertainment genres that would soon encompass most of the cinema and television of the future."[74]

By contrast, Wade, whose scholarship focuses on the natural history of vision, proposes that these devices be regarded as "philosophical toys"—a term commonly employed in the nineteenth century—because they served dual interests. "Philosophical instruments, like microscopes, were used to examine natural phenomena, but philosophical toys served the dual function of scientific investigation and popular amusement."[75] He suggests that the camera obscura was the first philosophical toy because of its applications to both art and science. Scientists and natural philosophers invented these optical devices to aid their inquiries into such visual phenomena as persistence of vision, stroboscopic motion, and binocular depth perception. Sir Charles Wheatstone, professor of Experimental Philosophy at King's College, defined philosophical toys as devices intended to illustrate and to popularize the principles of science. "The application of the principles of science to ornamental and amusing purposes contributes, in a great degree, to render them extensively popular; for the exhibition of striking experiments induces the observer to investigate their causes with additional interest, and enables him more permanently to remember their effects."[76] The devices originated at the hands not of carnival barkers but credentialed experimental philosophers. The optical devices helped advance experimental inquiries into vision. As Wade emphasizes, "The development of visual science was as dependent on these devices as biology had been upon the microscope."[77]

While visual persistence was an optical phenomenon that had been noted for centuries, the optical toys sharpened its study and its quantification and, via stroboscopes, connected it with the perception of apparent motion. His own investigations and experiments and those Newton carried out with color perception using prisms stimulated David Brewster to invent the kaleidoscope in 1816. He wrote, "When I discovered the development of the complementary colours, by the successive reflections of polarized light between two [glass] plates of gold and silver, the effects of the Kaleidoscope . . . were again forced upon my notice."[78] Influenced by Brewster's device and intending to illustrate visual persistence, Wheatstone created a sonic kaleidoscope in 1827 that he called the kaleidophone. He attached silver glass beads to rods which, when struck, made the beads vibrate and their reflected light to trace pleasing abstract figures in the air. Wheatstone wrote that his objective was to subject "to ocular demonstration the orbits or paths described by the points of greatest excursion in vibrating rods. . . . The entire track of each orbit is rendered simultaneously visible by causing it to be delineated by a brilliantly luminous point, and the figure being completed in less time than the duration of the visual impression, the whole orbit appears as a continuous line of light."[79] That same year, John Paris, a physician, devised the thaumatrope, a disk with drawings on each side which, when whirled, caused the drawings to be seen as one (for example, a rat inside a cage). Paris intended that the device serve a teaching function, illustrating the classics. Descriptions published in the early 1820s of stroboscopic illusions produced by counter-rotating cogwheels or by the spoke wheels of a carriage when viewed through a Venetian blind led to papers by physician Peter Mark Roget and chemist and physicist Michael Faraday analyzing the phenomena quantitatively and also to the invention of several varieties of stroboscopic disks. Faraday was a friend of Wheatstone's and was influenced by his interest in visual persistence, and his paper published in 1831 led to design applications. In 1833, after reading Faraday's paper, the Belgian scientist Joseph Plateau invented the phenakistiscope and Simon Stampfer, a professor of geometry in Vienna, created the stroboscopic disk. Similar devices, these disks held a series of drawings on one side separated by slits. When the disk was held before a mirror and rotated, and when viewed through the slits, the drawings appeared to move. Roget claimed that he had invented a similar device a few years earlier. In 1834, using the daedaleum (aka the zoetrope), William Horner placed drawings on a horizontal wheel rather than a vertical one, making it possible for several people to view the illusion at once. Scientists and natural philosophers studied the optical phenomena produced by the disks and noted the velocity and amount of light that were needed to produce the illusion.

In addition to visual persistence, Wheatstone was intrigued by more general questions about space and depth perception. He invented the stereoscope in 1832 after noting that retinal disparities increase as the eyes converge to focus on an object very near at hand. (Brewster invented a lenticular stereoscope a few years later.) He wondered if a similar experience of depth perception could be produced using plane images instead of three-dimensional objects. "What would be the visual effect of simultaneously presenting to each eye, instead of the object itself, its projection on a plane surface as it appears to that eye?"[80] He constructed the mirrored stereoscope in order to pursue a series of experiments into binocular vision that established for the first time its role in depth perception. Visual scientists before Wheatstone had noted the existence of retinal disparity, but it had not been connected with depth perception. The stereoscope enabled Wheatstone to investigate and demonstrate this connection. His device used mirrors to reflect paired line drawings of geometric forms. Using the line drawings eliminated the presence of monocular depth cues that could have confounded the results. He mounted the mirrors onto adjustable arms that enabled him to introduce variations into retinal size and retinal disparity and degrees of convergence and accommodation as elicited by the drawings. He thus was able to study these responses as separate variables. After William Fox Talbot's negative-to-positive photographic process was invented, Wheatstone had stereoscopic daguerreotypes made for the device.

The stereoscope also pointed toward a new and strange optical domain, taking its observer through a looking glass into a disorienting world. Wheatstone varied the device to create what he called the pseudoscope, which produced conversions of relief and depth. If the pictures in the stereoscope were transposed from one eye to the other, reversing the manner in which they were meant to be viewed, or inverted in other ways, an impossible world appeared. The interior of a teacup became a solid convex body. A globe of the earth became a concave hemisphere. "A bust regarded in front becomes a deep hollow mask. . . . A framed picture hanging against a wall appears as if imbedded in a cavity made in the wall." A flowering shrub in front of a hedge appears behind it. "A tree standing outside a window may be brought visible within the room in which the observer is standing." These strange perceptions were as of another world operating according to different physical laws. Wheatstone wrote, "With the pseudoscope we have a glance, as it were, into another visible world, in which external objects and our internal perceptions have no longer their habitual relation with each other." This fascination with novel visual experiences held a major appeal for the computer scientists who would write the algorithms that produced digital simulations of the phenomenal world, and the new vistas offered to audiences in such films as *Jurassic Park*, *Coraline*, and *Avatar* furnish much of their appeal. Indeed, as Anne Friedberg points out, this "fascination with virtuality," with visual approxi-



Sir Charles Wheatstone's mirrored stereoscope mations of the real, is exerted by optical devices from the camera obscura onward as the fundamental allure of extending vision in novel ways.[81]

Whereas the pseudoscope pointed toward new aesthetic experiences, the stereoscope placed the scientific investigation of vision onto firm ground. Wade notes that the stereoscope, "perhaps more than any other instrument, ushered in the era of experimentation in vision."[82] It pointed toward the cognitive components that operate in visual perception and also to the differences between eye and camera. Accommodation—the eye's ability to shift focus between near and far—is possible because the curvature of its lens changes, becoming more extreme with nearer objects, but a camera lens doesn't change its shape. Wheatstone's stereoscope could evoke accommodation responses from viewers according to changes in the positioning of its mirrored arms, and this offered one challenge to the camera-eye analogy. Helmholtz, who used an ophthalmometer to study more precise changes in accommodation, remarked on the differences: "A photographic camera can never show near and distant objects clearly at once, nor can the eye; but the eye shows them so rapidly one after another that most people, who have not thought of how they see, do not know that there is any change at all."[83] Mechanical devices such as the camera and the camera obscura could shift focus to different parts of a scene but not with the eye's swiftness or suppleness.

Wheatstone's stereoscope made important contributions to the empirical theory of vision, associated with Helmholtz, in distinction to nativist approaches that held that visual skills such as depth perception are innate and not subject to learning. Helmholtz studied the images produced by Wheatstone's stereoscope and used them to argue forcefully for the role of mind in vision. People do not see their retinal images, he maintained. They do not perceive a world that is upside down, as are retinal images. Moreover, how are the different retinal images combined to produce a single visual field seen in depth? He maintained that depth perception is a psychological rather than a physiological process, that vision involves an interpretive act rather than a strictly physical one. "The combination of these two sensations into the single picture of the external world of which we are conscious in ordinary vision is not produced by any anatomical mechanism of sensation, but by a mental act."[84] Wheatstone's stereoscope enabled Helmholtz and others to deepen their understanding of the perceptual processes involved in vision. The relatively intimate circles through which the art and science of philosophical toys and their associated inquires were pursued is illustrated by Helmholtz's attendance at an 1881 demonstration by Eadweard Muybridge of his zoopraxiscope, a projecting phenakistoscope that he used to show his series of photographs of horses in motion.[85] The event was held at the home of Etienne-Jules Marey, a physiologist who constructed numerous instruments, including cameras and projectors, for measuring animal and human motion. Marey had invited Muybridge to show his device to the leading scientists of the time.

The upsurge of vision research in the nineteenth century was an essential condition for the invention of cinema; the boulevard amusements and fairground attractions that often are described as the medium's roots should be ranked alongside the developing science of visual perception. But, as Lisa Cartwright points out, "The prehistory of the cinema is conventionally told as a tale of early scientific experimentation marked by a break with science around 1895 with the emergence of a popular film culture and industry."[86] No such breach has occurred. Art and science commingled in the invention of cinema, as they have continued to do in the decades since, most obviously in the digital turn that the medium has taken. The new toolbox available to filmmakers enhances their abilities to create artificial realms, evident in such films as *Lord of the Rings*, *Speed Racer*, and *Avatar*. But, as we will see, it also provides new methods for establishing perceptual and indexical modes of realism.

Viewing Pictorial Illusions

I close this chapter with a brief explication of the sophisticated nature of pictorial perception and by examining one of the book's fundamental questions, namely, whether cinema is best understood as being a photographic and therefore an indexical medium. Lev Manovich describes the "general tendency of the Western screen-based representational apparatus. In this tradition, the body must be fixed in space if the viewer is to see the image at all. From Renaissance monocular perspective to modern cinema, from Kepler's camera obscura to nineteenth-century camera lucida, the body has to remain still."[87] The immobilized spectator is taken to be a passive spectator, one who is positioned and worked over by the image.

While a cinema viewer does sit still in a seat to view a film, however, paintings are typically viewed in motion, by walking around them and glancing at them from several angles. Thus the viewer of a painting is not immobilized. More important, notions of a unified gaze are misleading. There are many gazes. Human vision operates by executing multiple, rapid glances, which are termed saccades. Because the fovea (the area of the retina that produces clear and sharp vision) is small, viewers must build up their sense of an overall picture on the screen of a film or the surface of a painting by taking many visual samples. Saccadic vision is a process of directive, goal-driven visual sampling. A viewer's phenomenal experience of an organic, unified space or visual field, in fact, is derived from a kind of perceptual montage, created from scores of rapid glances at salient areas of the picture. Saccades can be as quick as 30 milliseconds.[88] And the areas are not sampled in a linear fashion. The viewer's fovea makes saccadic jumps to very different, often widely spaced areas of the image, searching for salient details—highlights, faces, bright colors, movement—that can be used in making sense of the whole. The representational space in a perspective drawing may be unified, but the viewer's gaze is not—it is restless, multiform, successive, and analytic, constructing a mental image of the representation by sampling its visual information.

Moreover, the retinal disparity (differently angled images recorded by each eye) that produces binocular vision provides clear anti-illusionist cues that the surface of a painting or film is just that, a flat surface. If the viewer moves about, then the resulting motion perspective shows that the visual surface is planar. This is why the cinema viewer remains seated and why the optimum conditions for viewing a perspective drawing are with a person standing at the point of central projection holding one eye closed, a condition that is rarely practical or practiced. Thus the illusion of three-dimensional space produced by a representational image is limited. It is further constrained by the sharply reduced exposure latitude of a camera relative to the human eye and by the fact that the plane surface of a painting or cinema screen does not evoke vergence movements by the eyes as a viewer looks at objects represented at varying depths and distances in the pictorial space. And yet despite these limitations or failures of correspondence between human vision and representational imagery, the perceptual illusion of pictorial space still claims the viewer's attention. This suggests that the nature of pictorial illusion is more complicated than skeptical critiques may stipulate and that the viewer's role is more cognitively active and self-aware than accounts of spectators lured by spectacle warrant. M. H. Pirenne has discussed the limitations of painting and photography in duplicating or mimicking natural vision. After exploring numerous differences between the abilities of the eye to handle the information contained in light and what paintings and photographs can show, he concludes, "The alleged possibility of producing a complete, perfect, imitation of visible reality is a myth. The opposite belief, namely that there are no permanent optical laws relating to human vision, and that the evolution of art must be explained entirely on subjective grounds, for instance on the basis of varying concepts or intuitions of space, is another myth."[89] He emphasizes that the pictorial illusions offered by representational images are not simple. "Their perception is a complex process because it evokes in the spectator a special kind of awareness of the painted surface itself."[90]

This complexity of perceptual response furnishes us grounds for finding an aesthetic of realism in digital cinema images and for emphasizing the spectator's role as an active and complex one. As we will see, digital imaging tools provide numerous ways of replicating the optical principles involved in vision and in seeing a material world. Moreover, such complexity furnishes us with a reason for suspecting that the emergence of digital tools of image-making is less radical, disruptive, or threatening to the nature of cinema than is often thought. A common theme found in critiques of digital imaging is that it represents a break with cinema's analog heritage. Virtually all theories of cinematic or photographic realism proceed from the idea that a photograph is an index of the object or scene before the camera, that is, the photograph is a recorded trace of those things; it is causally and existentially connected with them. As David Rodowick writes in his important study of the shift in cinema from analog to digital modes, "Comparing computer-generated images with film reaffirms that photography's principal powers are those of analogy and indexicality."[91] The model of an indexical sign derives from the work of Charles S. Peirce, who devised the triadic schema of indexical, iconic, and symbolic signs. He noted that "photographs, especially instantaneous photographs, are very instructive, because we know that in certain respects they are exactly like the objects they represent. . . . They . . . correspond point by point to nature. In that respect, then, they belong to the second class of signs, those by physical connection."[92] Writing about photography, Roland Barthes claimed that photographs, unlike every other type of image, can never be divorced from their referents. Photograph and referent "are glued together."[93] For Barthes, photographs are causally connected to their referents. The former testifies to the presence of the latter. "I call 'photographic referent' not the *optionally* real thing to which an image or sign refers but the *necessarily* real thing which has been placed before the lens without which there would be no photograph."[94] For Barthes, "Every photograph is a certificate of presence."[95]

Most famously, André Bazin based his realist aesthetic on what he regarded as the objective nature of photography, which bears the mechanical trace of its referents. In a well-known passage, he wrote, "The photographic image is the object itself, the object freed from the conditions of time and space which govern it. No matter how fuzzy, distorted, or discolored, no matter how lacking in documentary value the image may be, it shares, by virtue of the very process of its becoming, the being of the model of which it is the reproduction; it is the model."[96]

The concept of indexicality has been used to suggest that digital images might create a rupture with photographic realism. For Lev Manovich, digital images strip away the medium's analog heritage, the "deposits of reality" that photographic images carry. "Cinema emerged out of the same impulse that engendered naturalism, court stenography and wax museums. Cinema is the art of the index; it is an attempt to make art out of a footprint. . . . Cinema's identity lies in its ability to record reality."[97] This premise—that cameras record reality—suggests one reason that visual effects have tended to fall outside of theories of cinema. Visual effects are composites, artificial collages, not camera records of reality. Digital images, too, can be taken as composites. As composites or manual constructions, digital images, for Manovich, threaten to return the medium to its own prehistory, to the hand-painted and hand-animated images that flourished in the nineteenth century's optical devices. "Consequently, cinema can no longer be clearly distinguished from animation. It is no longer an indexical media technology but, rather, a subgenre of painting."Jonathan Crary finds that digital images offer a fabricated reality rather than one that has been photographically recorded. The fabricated visual spaces of the digital realm split images from a knowable, observable reality. Everything can now be faked. "Visual images no longer have any reference to the position of an observer in a 'real,' optically perceived world."[98] For Sean Cubitt, digital media pose a crisis of meaning because they seem to "sever the link between meaning and truth, meaning and reference, meaning and observation. Digital media do not refer. They communicate."[99] He continues, "The digital corresponds so closely to the emergent loss of an ideological structure to social meaning because it no longer pretends to represent the world."By this he means that digital images lack photography's indexical connection to social and physical reality. Thus they do not represent that reality in the way that photography had.

By severing photographic images from indexical referents, digital imagery is said to pose a crisis for cinema, for photography, for a knowable reality as mediated by visual culture. As I hope to show in the pages to come, however, while digital tools have opened new expressive capabilities in cinema, they have not destroyed or broken with the old. Moreover, they have created new sources of indexical meaning that were never possible with analog photography. And notions of a break with cinema's analog heritage rest on a devotion to characteristics that the medium never truly possessed as dominant features of its style or structure. Bazin, for example, stressed compositional strategies that emphasized holistic space, achieved through the staging of action in depth and in shots of long duration. Cinematic realism lay there. "Essential cinema, seen for once in its pure state, on the contrary, is to be found in straightforward photographic respect for the unity of space."[100]

Narrative cinema has rarely respected unity of space as a basis for realism—except in the constructed manner achieved by such devices as continuity editing and selective framing with the camera. Cinema is an art of the fragment, composed of slices of pictorial space created at one moment in time and picked over by filmmakers and assembled into a new organization at a subsequent point in time. Aesthetic choices inevitably inflect medium-specific characteristics. The aesthetic and social objectives of filmmakers and the contexts in which images are created and circulate influence the degrees of realism attributed to visual images far more than whether they are analog or digital. The power of a John Ford western shot in Monument Valley derives from the compositional values Ford extracts from placing tiny figures among the looming sandstone monoliths of the location. It derives as well from a viewer's sense that the location is real, that is, it exists as an authentic space outside and beyond the camera's view. Gillo Pontecorvo's ability to re-create the Algerian war for independence in so apparently authentic a fashion in *The Battle of Algiers* (1966) was due in significant measure to his practice of shooting on location with crowds of people who had experienced the very things and emotions they were reenacting. Location filming exemplifies the kind of indexical value with which realism in cinema is frequently invested, namely, the camera's ability to record images that are isomorphic with the spaces that were before the lens. Critiques of digital imaging suggest that because digital images can be invisibly manipulated, a viewer cannot trust the image or know that an authentic location is really that. But nothing precludes a filmmaker from working digitally and shooting on a real location if the authenticity of a locale is aesthetically important. Debra Granik's *Winter's Bone* (2010) was shot in winter on location in the Ozark Mountains to achieve the visual authenticity called for in the story, and the filmmakers spent two years before the shoot researching the area and scouting locations. It was shot digitally, with images captured using Red One cameras. Its aesthetic use of location makes the same claims to indexical realism as *The Battle of Algiers*.

To return to my earlier point, even when authentic locations are part of a film's aesthetic design, unity of space is most often a manufactured impression. For a key dialogue scene in which characters take a boat out on a pond to retrieve a body, Granik shot on dry land and used low camera positions to hide this fact. John Ford's cutting in *The Searchers* (1956) conjoins locations in Monument Valley that are not adjacent to one another, and he intercuts location shots with studio sets. As Lev Manovich points out, "Traditional fiction film transports us into a space—a room, a house, a city. Usually none of these exists in reality. What exists are a few fragments carefully constructed in a studio."[101] He perceptively notes that in the digital era "the problem of realism has to be studied afresh."[102] In doing so, we will find that aesthetic and stylistic practices in cinema have changed little and that the differences between analog and digital cinema do not form a stark divide.

Cinema *is* a composited medium, whether analog or digital, and this singular condition has been undervalued in our existing theories. Visual effects are at home in a composited medium, not incursions or intrusions therein. Keeping this condition in mind is fundamental to our ability to understand digital effects and the ways in which they are organic manifestations of narrative cinema's essential features. Overcoming the profilmic space—reorganizing it, reimagining it—is essential to the tradition of fiction in cinema (and also in many ways to the mode of documentary where filmmakers often feel the need to find a story and tell it). A fictional world established on screen is a synthetic creation, an amalgam of various physical continuities created in the editing along with emotional elements created by actors, editors, cinematographers, and directors that are deemed to be true to the scene as depicted. It is also an amalgam of visual effects techniques. On this basis little changes as we move from analog to digital. Thus we will need to find other bases for an aesthetic of realism than the models proposed by Bazin or derived from analogies with photography. Helmholtz's idea of vision as an interpretive act can serve us well here. As Helmholtz noted, the properties of a creative medium entail that "the artist cannot transcribe nature; he must translate her."[103] As I hope to show in the pages to come, digital tools are best understood not as applications undermining realism but as modes of translation—seductions of reality—designs for creating new extensions of realism and fictional truths. When the T-Rex gobbles Martin off the restroom toilet, the staging of the action in a single framing creates a vivid continuity of digital and live action space, prompting a new interpretive response from viewers, as does Jake Sully's stereoscopic transformation from a crippled marine to a seven-foot-tall Na'vi warrior in *Avatar*.

Rather than dismiss these juxtapositions as inconsistent with a realist aesthetic, I prefer to explore them as cinematic extensions of the senses and the imagination, extensions that are achieved through a new technology. Philip Steadman explained Vermeer's use of the camera obscura in such terms. He describes how its single, uncorrected lens fails to achieve perfect focus over a large area and transmutes the three-dimensional scene that the artist could observe with his eyes into a two-dimensional array of overlapping planes. The relative dimness of the camera's image and the translucent screen or paper onto which Vermeer traced his composition obscured detail and made objects distinguishable according to shape and tonal value, but these distinctions no longer corresponded to discriminations that the eye

Visual effects images frequently present viewers with optical extensions of the senses and the imagination and can be used to design wholly new worlds, as in *Avatar* (2009, Twentieth Century–Fox). Frame enlargement.

would make. "It may then happen that some of these boundaries do *not* fall at the edges of objects in the scene. Vermeer starts to paint patches of light and colour, not fingers or bodices or violas with the forms and outlines by which they are mentally conceived."[104] The camera obscura provided him with a new way of seeing, disentangled from the mental habits induced by ordinary vision, and gave Vermeer a means for achieving the strange combination of tonal clarity and dissolution of line and form that distinguishes his late style. Steadman speculates that these aberrant visual characteristics were exactly what intrigued Vermeer: "The camera allowed the artist to enter a newly revealed world of optical phenomena and to explore how these might be recorded in paint."[105]

John Whitney emphasized, "Geometry and reality are not disparate entities, one cold and impersonal, nor is the other all that lovable, of course." The diversity of life and matter throughout the universe merely was an expression of "the 'idiosyncrasies' of geometry." And computers opened new possibilities for artists and scientists to capture this. "Computer geometry, infinitely diverse, as in nature itself, constrains graphic diversity merely as a limit of resolution," wrote Whitney. "The higher the resolution, the greater the visual diversity."[106] To artists and scientists in earlier centuries, the camera obscura opened up a new optical domain and made it available for study and exploration. Computer graphics and digital imaging are doing so now. Ivan Sutherland, one of the pioneers of computer graphics, felt something of Vermeer's excitement. "A display connected to a digital computer gives us a chance to gain familiarity with concepts not realizable in the physical world," he said. "It is a looking glass into a mathematical wonderland."[107] Loren Carpenter's *Vol Libre* revolutionized computer graphics by demonstrating the power of fractals for generating animated organic forms. He had a Ph.D. but didn't want to teach. He wanted instead to see new optical worlds. "I wanted to see my imagination. And I wanted to see other people's imagination. And so in order to do that, I worked hard to give people the tools."[108] Digital images take viewers through the looking glass into new landscapes of vision unavailable to ordinary sense, enable them to peer into domains of the imagination. In the process, they have given filmmakers new methods for extending the aesthetics of cinema. The next chapters show how.