Technological Developments in Computer Art from the Mid-20th Century to the Present

This paper recounts the history of important milestones in computer art, including pre-digital influences and imagery created with electronic/new media and analog computers, specifically built for that purpose. Particular emphasis will be paid to the people, places, tools, and techniques developed in the 1970s and later, many of which are still integral to computer art today. Significant works of imagery, animation, and visual effects will be presented in the context of a historical timeline, culminating in the release of the first fully computer-animated feature-length film. Developments in realism continued that continually blur the line between the real and the unreal.

All art depends on technology. It is closely linked to the specific artist's educational level, but also more generally to the cultural advancement of the time. It can be argued that from the very beginning, technological innovations enhanced what could be achieved aesthetically and the stories that could be told. From hollow bones used to blow pigment on the earliest of cave paintings, to the myriad of mediums, surfaces, and implements employed by the masters of the Renaissance, visual art has depended on tools. Better tools mean a better end result. Even such technological leaps as printmaking, which puts a certain degree of automation and distance between the artist and his artwork, only expanded and enriched the art world. Great artists such as Rembrandt used this tool to create what could not be done otherwise and turned etchings into one of the great art forms. Masterpieces could be found in editions and series, not just unique originals. Whether evolutionary or revolutionary, accepted or rejected, technology and new media have always ultimately been beneficial to art.

The same pioneering techniques in painting, drawing, sculpting, and printmaking developed centuries ago are still in use today by a wide range of artists. Advances have been cultural and societal, however, the technology has remained constant. A change to this long history appeared early in the 20th century: art that was closely linked with new technology. The Bauhaus movement in Germany was an environment in which a new aesthetic for modern times could evolve. Not only did new styles in color, design, and typography emerge, created by artists and students of the Bauhaus, but modern architecture and industrial design appeared as well, influenced in no small part by the application of new fabrication techniques and materials like glass, steel, and plastic. Even found and discarded materials, chosen because of wartime restrictions, were utilized. The resulting work was items designed for everyday use by the common man, not luxuries to be owned and appreciated by the elite. This same approach to new methods of creating art would soon bring us the beginnings of computer art.

In 1952, Ben Laposky used an Oscilloscope to create what may be the first example of new media art.[1] *Oscillon 40* was part of a series of images created with this unexpected tool. The final pieces were actually time-lapse photographs of the oscilloscope's small screen, taken in a dark room. By adjusting the equipment settings, Laposky created many varied and new designs, eventually adding color. Another technological advancement, photography, would be required for many years as imagery that could be created electronically had no output devices to get beyond monitor screens.

John Whitney, Sr., known as the father of computer graphics and animation, used a mechanical analog computer he built to create his artwork. In the late 1950s, he utilized the mechanism from a WWII M-5 antiaircraft gun director as the brains of what would end up as a 12-foot high machine of his own creation.[2] Originally designed to calculate the lead for large guns to shoot down enemy planes by calculating speed, distance, and other factors, in Whitney's hands, these tools of destruction became instruments of creation as they powered rotating tables and controlled cameras to create intricate, complex designs that could never be done by hand. In

1958, his animated visuals would be integrated by award-winning graphic designer Saul Bass in the revolutionary title sequence of Alfred Hitchcock's *Vertigo*.[3]

While perhaps not computers as we would understand them today, the machines Whitney used in his films were pushing the boundaries of what cameras and optics could do, creating a whole new genre of animation. He also came up with a technique he called 'slit scanning,' which used an animated camera, tracking toward backlit artwork showing through a narrow slit in an opaque material. With the exposure opened, he was basically painting with animated light. The result was something that hadn't been seen before, with endless possibilities of movement, shape, and color. The most famous example of this technique is found in the Stargate sequence of *2001: A Space Odyssey*, released in 1968.[4] The mind-blowing visuals of this film changed the way science fiction movies were made and raised the expectations of viewing audiences.

Whitney would continue to experiment with and create computer imagery for the rest of his life, his work evolving as the technology did. Important animations of his from this time period range from *Catalog* (1961) to *Matrix I* (1971). Recognizing the value of these experiments, IBM awarded him its first artist-in-residence position in 1966.[5] By the 1970s, he had embraced new digital technologies, leaving his slower, analog process behind. A high point of his work from this period is *Arabesque* (1975), a 7-minute film of abstract animation set to music, with collaboration from Larry Cuba. Although not a musician, Whitney later began creating digital sounds on his computers as music to complement his new graphic animations. In 1972, he taught the first computer graphics course at UCLA.[6] His sons followed in his footsteps through the digital revolution.

Another 'father of computer graphics' is Ivan Sutherland, visionary computer scientist, as practically all computer artists needed to be at this time. His invaluable contribution is

Sketchpad, a program he wrote in 1963 as part of this PhD thesis, and which eventually won him the Turing Award.[7] It ran on a Lincoln TX-2, built in 1958 at MIT. Using a recently-invented stylus called a light pen, Sutherland drew directly on a monochromatic cathode ray tube (CRT) monitor to create vector geometric shapes. Designs could be easily scaled, copied, moved, and arranged to create complex, accurate schematic layouts. This was the first computer program with a graphic user interface[8] and could be seen as the precursor to modern CAD programs, and eventually vector-based drawing and 3D programs. He would go on to found Evans & Sutherland, one of the first companies specializing in computer graphics.

The other half of this company, Dave C. Evans, returned to the University of Utah as a professor in 1965 to start their Computer Sciences department. He also recruited Ivan Sutherland to assist him, who came to Utah on the condition that they start a computer graphics company together.[9] This unassuming department at the U of U would eventually produce some of the most important players in the field of computer art, who developed tools and techniques we are still using today in the highest levels of computer graphics, animation, and visual effects.

The field of computer art appears to be replete with many 'firsts' and 'fathers.', Charles Csuri, considered by many the father of computer art and animation,[10] was a traditional painter who entered the computer world at Ohio State University. With only one computer on the entire campus and no graphics software, he had to create artwork by programming in Fortran. The result was a series of paper punch cards which contained the data to run a drum plotting device. He created his first example of computer art in 1964 and kept on from there. By 1967, he was creating animations and in 1968, made *Hummingbird*, an experimental film of over 30,000 frames,[11] which took a plotted line drawing of a hummingbird and exploded the segments, breaking them apart and reforming them. Punch cards and an IBM 1130 were used.

An important milestone in the physical output of computer-generated imagery has an amusing backstory. Because of the cost and size of computers in the 1960s and earlier, only large institutions like major corporations, governments, and universities could afford them. One of these at the time was Bell Laboratories. In addition to providing telephone service, they used their considerable resources to research emerging technologies, including lasers, printers, and computers. In 1967, Ken Knowlton and Leon Harmon were among the first to scan and print a photograph, rendering it with ASCII characters representing the image's tonality.[12] The problem is that they chose to scan and print a photograph of a reclining nude. Worse yet, they printed it out as a 12-foot-long banner and hung it up on a colleague's office wall as an admitted 'sophomoric prank' while he was away. The image was an abstract jumble of symbols when viewed close up, but from a distance, the subject was immediately discernable. While the act was appreciated, after only a day, it was taken down and retired to a less-visible basement location.

Notwithstanding this safeguard, reproductions of the image soon began circulating around the offices. Word came down from management that it was acceptable to disseminate the print, but it should not be associated with Bell Labs in any way. However, the print was later exhibited at an art and technology event held at Robert Rauschenberg's loft and on 11 October of that year, was featured and prominently pictured in a New York Times article.[13] By that time, it had been given the rather lofty title of *Computer Nude (Studies in Perception I)*. With this veneer of acceptance and respectability, the image's significance radically shifted for management. A new memo was sent out company-wide, reaffirming that sharing the image was acceptable, but this time, make sure that everyone knows it came from Bell Labs.[14] A smaller version of the print was displayed at the Museum of Modern Art in New York City. Limited edition prints have been made, and the original has been sold for thousands of dollars.[15]

Largely ignored or even dismissed by the art world, computer graphics soldiered on, pushed forward by a small number of iconoclastic pioneers. The technologies and techniques were improving and advancing, but toward what end? The answer would come from an experimental group at the New York Institute of Technology's (NYIT) Computer Graphics Lab, founded in 1974 by Dr. Alexander Schure, a wealthy entrepreneur. He had the unlikely goal of creating a feature-length film, animated with computers.[16] To staff his project, he traveled the country, seeking the best minds in this fledgling discipline. Dave Evans of Evans & Sutherland suggested Ed Catmull at the University of Utah as the likely choice to head the department.[17] Their Computer Graphics Division had been quietly making major advancements in realistic computer-generated imagery.

Returning to the University of Utah as a graduate student in 1970, Ed Catmull studied under Ivan Sutherland. Long inspired by Disney animated movies, he didn't quite have the artistic aptitude necessary to be an animator, so he dedicated his efforts to math and computer science. Believing Sketchpad to be the start of a new method of animating, he worked to combine his two great loves, animation and technology, toward the goal of making a full-length computer animated movie. In 1972, he created *Computer Animated Hand*, a short animated sequence.[18] He started by making a cast his own hand, however, he was not aware of the correct procedures to this and failed to take precautions for the fact that body hairs are caught in the plaster and painfully pulled out when it hardens. He then drew about 350 triangles on the resulting model and digitized it in 3D space. These data became 3D geometry, which he animated and lit with smooth shading. This small clip, along with others, was later used unchanged as a display on a background monitor in the 1976 film *Futureworld*.[19]

Also at the U of U, Henri Gouraud wrote “Computer Display of Curved Surfaces,”[20] a method of shading to give more realism in 1971, giving rise to the shading algorithm that would bear his name. Rendering straight lines between points was an easy feat for computers at the time, curved surfaces being the real problem. Bézier curves had already been invented, but meshes of Bézier patches in 3D surfaces were difficult to render. To combat this, Catmull wrote “A Subdivision Algorithm for Computer Display of Curved Surfaces” in 1974.[21] In developing bicubic patches as a solution, he inadvertently discovered texture mapping.[22] He is also credited with the invention of the z-buffer, although this concept was described a few months earlier by Wolfgang Straßer in his PhD thesis.[23] In 1975, Bui Tuong Phong published “Illumination for Computer Generated Pictures,”[24] detailing his more advanced and realistic shading method, again providing the name for a now commonly-used technique.

All of these innovations developed at the University of Utah in the early 70s relied on raster graphics, intrinsically tied to the limited resolution of contemporary monitors. Anti-aliasing existed as a solution to soften jaggy edges, but Catmull would later develop additional algorithms to improve spatial anti-aliasing. However, by 1974, he had found no professional opportunities to apply his groundbreaking achievements. Computer generated imagery was still a tool in search of a purpose. Giving up on his dream, Catmull took a job at a CAD/CAM company to support himself and his family. Such was his situation when Alexander Schure found him. Accepting the offer of director at NYIT’s Computer Graphics Lab was an easy decision for Catmull and Schure’s dream began to take shape.

With Schure’s financial backing, the lab was never lacking for the latest and most powerful computer hardware. Any request was granted, no matter the cost,[25] much of it coming directly from Evans & Sutherland, the biggest name around for computer hardware. Ed Catmull directed a very open organization, bringing in associates from the U of U, Xerox's Palo Alto Research Center (PARC), NASA's Jet Propulsion Lab (JPL), and Evans & Sutherland. For a couple of years, they invented new technologies such as RGB images, bump mapping, alpha channels, soft edges, pixel dissolves, networking, and more, all while creating new and more complex computer art in the form of stills and animation.[26] Traditional artists there were working on their animated feature, *Tubby the Tuba*, based on a 1945 children's story. Schure acted as the movie's director, but without anyone involved having the necessary skill and experience to create a movie like this, the end result was terrible. The only consolation for Catmull and his group at the lab was that none of their work was used in the final film; it all ended up being traditional art and animation.[27] Computer graphics were used for some commercials and test reels were made in search of other paying work to generate revenue for the lab.

In 1979, a call came from a representative of Lucasfilm. George Lucas was interested in seeing what computers could do for filmmaking.[28] Oddly enough, the Star Wars movies, while being on the cutting edge of special effects, were hardly using computers at all, aside from computer-controlled cameras for bluescreen shots. An outside computer artist, Larry Cuba, had been contracted to create the 3D linework animation of the Death Star trench on the first movie.[29] For *The Empire Strikes Back*, no computer generated imagery was used at all. Lucas' interest in computers was to simplify and improve the overall filmmaking process in editing, sound, and compositing. Ed Catmull was singled out as the best candidate for this new opportunity and the lab already had examples of computer art that impressed the effects team at Industrial Light & Magic (ILM).[30] Catmull passed ILM's test and left NYIT to become the head of Lucasfilm's brand new Computer Division. But he and all interested parties had to go about things very quietly. Anyone investigating outside opportunities was immediately fired by Schure.

The prospect of leaving to work at the same studio making Star Wars was too irresistible a prospect for the artists at NYIT's Computer Graphics Lab, but they had to proceed cautiously to not leave en masse and provoke a panic in the lab. Gradually, interested programmers and artists left one by one, 'laundered' themselves temporarily at other computer jobs, then went to Lucasfilm in northern California. Even though George Lucas had no plan to use computers to create films or special effects, Catmull and others felt that they had exhausted their possibilities at NYIT and that Lucasfilm offered a better chance at pursuing their goals.

Without any computers yet to work on, Catmull set up shop. Alvy Ray Smith, who had worked on 2D paint programs at Xerox PARC and NYIT, was chosen to work on digital compositing. The problem of going from screen to output loomed large. Filming the CRT screens would not produce footage of high enough quality. Film needed to be scanned at high resolution and then images from the computer had to somehow get back to film. Setting these concerns aside, Catmull and his team hired the best and most innovative computer artists they could find, attending SIGGRAPH every year. In 1981, the opportunity arose to put these skills to the ultimate test when Paramount Pictures hired ILM to create visual effects for *Star Trek II: The Wrath of Khan*.[31] Catmull got approval from effects supervisors to create the Genesis Project animation. Their limitations of not being able to work at film resolution, only video, served them well, as the animation was supposed to be seen on a monitor in the film. Smith drew upon his work at NASA's JPL and the camera motion used by Lucas in his movies. Particle systems were developed and used for the first time. The sequence was deemed a success at its test screening. Lucas himself commented, "Great camera shot!" and did not seem to notice the CG imagery.[32] While this was not the first time computers had created imagery for movies (*Star Wars*, *Alien*, and others, including Catmull's own sequence in *Futureworld*), it was arguably the most dramatic and cinematic. Still, Catmull was concerned about the lack of realism in the motion; it needed blur from the camera movement to achieve the level he really wanted.

Catmull continued to give talks and show their new technical achievements at conventions, but was really trying to make an animated story. He met John Lasseter, a young animator recently fired from Disney, at SIGGRAPH in 1983 and was urged by Smith to hire him on the spot. Concerned that Lucas would not see the need for an animator in his technical Computer Division, they gave him the title of 'interface designer.'[33] Working feverishly on the short story *André and Wally B.*, the team took every advantage of Lasseter's traditional animation experience. Although basic primitive geometric shapes were all that was available, Lasseter found ways of combining them into relatable characters. He employed traditional animation techniques such as squash and stretch, follow-through, and anticipation. The color palette was inspired by Maxfield Parrish paintings. Technical developments finally gave Catmull the motion blur he was looking for. At less than two minutes, the animation had to be rendered on two Cray X-MP supercomputers and it still wasn't quite done for the 1984 SIGGRAPH; a few shots used Lasseter's pencil tests.[34]

The world premiere of *André and Wally B.* was in Minneapolis. Better yet, word got out that George Lucas was flying in to see it. Everyone involved was elated, but it probably had more to do with the fact that his girlfriend at the time, Linda Ronstadt, was performing there about the same time. But they both came, arriving with Catmull and Smith. To avoid a big scene, their limousine drove into an underground lot and they entered the theater after the lights had gone down. The audience response to the short was immediate and overwhelming; everyone loved it, responding with intense applause and yells. They all wanted to know how it was done.

Lucas was polite at the time, but he actually hated it.[35] The film convinced him that his Computer Division shouldn't be making movies and the die was cast for its ultimate demise.

Such is the history of what is now considered the first of Pixar's many award-winning shorts. In an attempt to keep the division viable, the group unveiled hardware it had developed: The Pixar Image Computer. Ostensibly, future shorts would be marketing vehicles to promote the Pixar, but it was never that commercially viable. Actually, it was barely used in the creation of the animations,[36] although each one pushed new boundaries in the field of realistic 3D graphics. It would take outside investors with serious funding (Steve Jobs, for example) for the animation group to break away and eventually become what it really needed to be: Pixar Animation Studios. In 1995, Ed Catmull's (and many others') dream was finally realized with the release of *Toy Story*, the first feature-length, fully computer-animated film.

Based on Catmull's idea that anti-aliasing was more important than larger resolutions in solving the problem of jaggies visually, *Toy Story* was rendered was rendered at a frame size of just 1536x922 pixels. The computing power to render final images was daunting for the time: a render farm of 117 linked computers working continuously took up to 20 hours per frame on the most complex scenes, totaling over 110,000 frames in the final film.[37] While this pixel size may seem small, current render sizes for animated movies and digital visual effects today are not much larger, usually done at around 2K (2048 pixels wide). Blinn's Law states that as processors increase in speed and power, render times will not decrease because computer artists create denser and denser images as improvements in graphics technology allow for more realistic imagery.[38] Indeed, the number of computers in render farms and render times themselves have been steadily increasing.

While the plastic toys in *Toy Story* were the perfect subject for the state of rendering full frames at the time, the goal has always been realistic, organic living creatures and characters. By comparison, its living people and animals seemed less emotive and 'alive' in some ways than the toys. Realistic computer-generated creatures that could hold their own against live actors and environments had already been achieved in 1993 with the release of *Jurassic Park*. Originally realized through the latest advances in stop-motion (called go-motion by its developers), the dinosaurs needed to achieve a level of realism not seen before. Although early tests were impressive, when Spielberg saw an animated render of a walking Tyrannosaur that ILM's computer artists had created, it was the obvious choice; stop-motion immediately became antiquated and the creature effects industry changed forever.[39]

Even though it came out earlier, *Jurassic Park* hit a pinnacle of realism in computer art that still holds up decades later. Given the limited resources at the time, its accomplishment is still unparalleled. Top-of-the-line software such as Softimage and Alias were used to create the 3D geometry, built using NURBS. In addition to bump maps, displacement maps that actually deform the geometry were used. In 1996, Venkat Krishnamurthy and Marc Levoy published a paper on this technique as SIGGRAPH.[40]

Although they use some off-the-shelf programs, ILM often develops their own proprietary software and pipelines internally. In 1992, Graphics artists and programmers there were working on their own to create a more interactive paint program for 3D models. They had been using an internal program called Layerpaint, but it did not have the capabilities they needed, so they combined elements from a commercial paint program called Matador with Viewpaint, developed internally by John Schlag and Zoran Kacic-Alesic, which was designed to be more artist friendly than previous software packages.[41] The end result was a tool that digital artists could use to paint skin texture directly onto the virtual dinosaur models.

As with Pixar, ILM did not rely solely on the latest technology for its award-winning visuals. Even though traditional stop-motion animator Phil Tippet, who had been bringing creatures to life at ILM since the first *Star Wars*, felt he and his skills were now 'extinct' like the giant reptiles, his invaluable expertise still was needed, like Lasseter's. To take advantage of his knowledge, ILM effects supervisor Dennis Muren and Craig Hayes appropriated the armature of a physical stop-motion puppet, giving it inputs to translate its physical movements into digital data, thereby creating a Dinosaur Input Device, bridging the traditional with the digital. Rick Sayer from Pixar was brought in to assist in its construction.[42] The traditional animators could now apply their trade in this new realm. Rather than face extinction, they could choose evolution.

An important milestone in computer imagery occurred the following year with the release of *Forrest Gump*. Instead of creating fantastic imagery never seen before, computer art now created a new reality with its historical footage, missing legs, super fast ping-pong, background crowds, and more. Some of the magic is obvious (Tom Hanks did not really shake hands with President Kennedy), however, there are so many scenes altered for practicality or safety that it becomes impossible for the casual viewer to distinguish what is real and what is not.[43] The tools of digital chroma keying, compositing, image warping, and rotoscoping were not revolutionary or new, but their implementation certainly was. While we can rationally dismiss the dinosaurs of *Jurassic Park*, *Forrest Gump* proved once and for all that we can never again believe what we see on film.

As groundbreaking as *Jurassic Park*'s dinosaurs were, they did not really act. They were animals, not personalities, but Dennis Muren hoped that filmmakers would see the potential to create characters.[44] In 1999, the first serious attempt was made to create a realistic CGI character, or virtual actor, in a live action movie in *Star Wars: Episode I - The Phantom Menace*. Ironically enough, Jar-Jar Binks was initially designed to be a hybrid effect, with an actor in extensive costuming portraying the character and the head being replaced with computer animation. Although markers were placed around the neck of the costume for tracking, the task of removing the real head and solidly matching the actor's motion with the CG animated version proved too difficult and time-consuming to do realistically and believably. It turned out to be more efficient to replace the entire live character with a completely computer generated one, with the actor reprising his role in a motion capture suit as needed. The $100,000 spent on the costume was not completely wasted; it provided useful reference to the computer artists for accurate lighting and rendering.[45]

As a digital character, the success of Jar-Jar Binks is mixed (at best) on many levels. In comparison, universal acclaim is given to the character of Gollum from *The Lord of the Rings: The Two Towers*, released in 2002, who became the first virtual actor to win an award. The human actor provided not only the voice, but also the movements, on-set physicality, and personality of the character. As with previous attempts to create a digital character, motion-capture filming, rotoscoping, and hand animation were used.[46] Digital techniques that had become standard are always being improved, refined, and streamlined, but something completely new was put into the pipeline for Gollum.

Near the end of 1998, computer graphics researcher Henrik Jensen noticed that light diffused or passed through surfaces. He later teamed up with Weta Digital's visual effects supervisor Joe Letteri to implement this principle in the skin textures for Gollum, the first digital character to benefit from subsurface scattering.[47] Weta also wrote their own proprietary software to mimic the natural movement of muscles under the skin,[48] as the character was emaciated and barely clothed, so the movement of soft tissue would have to be convincing. The result was, as animation design supervisor Randall Cook had hoped, the benchmark against which all CG characters would be judged.[49] With all the continued advances in computer art over almost 20 years, this is still pretty much the case. Because of this accomplishment, MTV created a new category, Best Virtual Performance, awarding it to Andy Serkis, the actor driving the performance.[50] Other awarding groups would soon follow suit, recognizing this new technology.

As computer artists conquer more and more visual subjects, rendering them photo-realistically, the line between the real and the unreal keeps getting blurred. Perhaps the last hurdle, the holy grail of computer art, was to believably recreate a known person. Such was the challenge tackled by ILM's digital artists with the release of *Rogue One: A Star Wars Story* in 2016. Ethical issues aside, the decision to feature Grand Moff Tarkin in such a prominent role was a bold one, enabled by a new facial pipeline, which actually originated with an earlier film, *Teenage Mutant Ninja Turtles*, and continued to be refined throughout subsequent movies featuring CG characters extensive facial and talking animation.[51] Luckily, a facial mold of Peter Cushing made in 1984 was still extant,[52] so the 3D geometry could be extremely accurate.

Guy Henry, the actor portraying Tarkin and impersonating Cushing, wore a head rig with four cameras on set that captured his facial acting, recognizing the myriad of dots painted on his face and allowed for a 3D digital reconstruction of his movements. Applying this animation data to the Tarkin model was more difficult than might be apparent, as Henry's facial movements are different than Cushing's. Naturalistic mouth movements are notoriously difficult to get right. To bridge this gap, Kiran Bhat and Michael Koperwas developed SnapSolver, another ILM proprietary program, for earlier movies.[53] By the time *Rogue One* was in production, this pipeline was a well-oiled machine, ready for its greatest challenge. Reaching this particular benchmark has been attempted many times, and only a slight failure results in the 'uncanny valley.' Whether or not ILM's digital Tarkin is successful may still be a matter of debate, but it is arguably the best so far.

Not coincidentally, these most recent examples are not within the realm of fine art or gallery exhibits, but rather, belong to the popular culture vehicle of movies aimed at mass markets. No longer masterpieces to be hung on gallery walls and admired by a select few, or purchased by even fewer, digital art has become art for the masses that anyone can enjoy for the price of a movie ticket. In the modern age, the cinema has replaced the gallery or museum in this latest form of new media art.

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