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A History of Computer Animation

Computer animation emerged as a viable technology during the early 1960's as the still evolving digital computer was coupled with increasingly sophisticated graphical output devices.

Depending upon what you decide is animation and what you decide constitutes a computer, it is easy to conclude that *all* animation is "computer" animation. The reason is because even classical (pre-computer) animation involves an animation language—a notational system which describe events or images over time. In a classical system, the instructions and graphical data are composed on paper, and the hardware execution is accompanied by an animation camera and camer operator—sort of a hardware/bioware combination. In a contemporary system the instructions and graphical data are composed on magnetic media, and hardware execution is accompanished by a computer automatically.

If we restrict ourselves to the post-classical phase of the medium, the first computer animations emerge in the early I960s, depending on what you mean by a computer and by animation. The fundamentals to achieve this and milestones are detailed in sections on motion control, CRT and raster graphics, hardware and media approaches, and increasingly sophisticated software simulations of line drawing, drafting, imaging, perspective, color, opacity, lighting, and textures.

Finally we review how time, the subject of our first chapter, emerged as a varible, and take a careful look at the key features of animation language, both before the computer as well as how they have evolved in processes like motion control, 3D lens and camera simulation, communications between temporal events, and editing (fig. 1).

The Origins of Animation

Animated phase pictures and roll media (1828-1895)

Animation predates the motion pictures and was a popular entertainment during the 19th century and sold by the thousands to the households of the industrial age. These animated phase pictures—short cycles of animation—were marketed on both disk and cylinder machines. The disk machines, such as the **phenakistiscope** (1828), arranged the series of discrete images

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1. Control pannel shows themes leading to the discovery of computer animation. [Jud's Hypercard art].

radically (fig. 31). The cylinder machines, like the **zoetrope** (1832) mounted a paper band of images on the inside of a drum. The media was then spun and viewed through slots in media.

Parisian Emile Reynaud opened the first movie theater, *Theater Optique.*, and began projecting animated movies created by drawing individual frames on rolls of paper (1892). His roll media expanded animation sequences from short, second-long cycles to longer scenes, and his projector changed the audience from one viewer (or at best, a few) into an audience of hundreds, recreating the proscenium [sp] stage.

Photographic roll film media began to be manufactured in 1888 by George Eastman, the founder of Eastman Kodak Company. Just before the turn of the century Thomas Edison in New Jersey (1889), and the Lumiére brothers in Paris (1895) successfully fused photography with the moving picture, solving both the recording and projection problems.

Thus as the phase cycles of disc, cylinder and paddlewheel media gave way to longer format roll media, and as the single-viewer peep show gave way to the projector and the multi-viewer movie theater, two media variables changed radically: The axis of time increased dramatically in magnitude, and the medium changed from individualistic to audience oriented. The integration of a moving picture photography and projection system catalyzed the process and purpose of animation, and during the next two decades many of the basic concepts of the medium were developed and deployed.

The early trickfilmsters and technology (1895-1909)

The first generation of the celluloid cinematographers included documentarians makeing observational films, trickfilmsters like magician Georges Méliès, lightning cartoonists like J. Stewart Blackton, and newspaper cartoonists, like Emile Cohl. The first films, like *Fred Ott's Sneeze* (1894) depicted short single action scenes, but by 1896 the Lumieres had dispatched crews around the world to make "observational films" and before the turn of the century the camera was panning and being mounted on vehicles and boats. In 1903 cinematography was married to the story, as Edwin S. Porter introduced cross cuts and parallel action into *The Great Train Robbery.*

It is convenient to identify three technical paths of motion picture development. The first is **live action**, which records real people and places, or actors on sets, using a (moveable) camera that records in real time. The second is **animation**, which employs discrete drawings or adjustable physical 3D models, and a static, single frame (stop motion) camera. Animation is not recorded in real time. The third is **trick film**, which combines both of these techniques along with a host of processes indigenous to the medium itself. The trick film especially uses cinematic vehicles (aka special effects) to create an illusion.

Edison's first trick film, probably directed by William Dickson, dramatized *The Execution of Mary Queen of Scots* (1895), and was a box office sensation (fig. 2). The seemingly completely realistic beheading was accomplised using a technique called the **arret**, a technique that involves stopping the camera, moving actors, props, or artwork, and restarting the camera.

The arret was used by all the early trickfilmseters including Blackton (1898), Booth (1906), and Chomon (1905), but nobody explored the physics of the new media better than Parisian George Méliès, a vaudeville magician who built a camera/projector and began making and exhibiting trickfilms. In his shorts, Méliès incorporated not only elaborate drawings and moving props into the set, but also a plethora of camera tricks. Legend has it the arret was "revealed" to Méliès when he screened a reel that had been stopped and then restarted on a street with moving traffic.

The arret is not quite animation, but a series of arrets, or **single frame** (aka stop motion) photography, become the basis of making animation, regardless of whether you are shooting 2D drawings or 3D objects. Just to what extent which of the pioneers used single frame photography is uncertain, because some of the pre 1900 model photography was accomplised using invisible wires and was shot live action. But in 1907 two films by J. Stuart Blackton firmly established animation—one with blackboard drawing and the other with models. Once the gene is out of the box single framing is widely employed, and instigates the traditions of animation using clay, 2D silhouettes and cutouts, and 3D model animation.

Another early development was single frame photography of the progressive development of a single drawing, usually today called a **scratchon**. The scratchon was evolved by lightning sketch vaudville artists like Blackton, who drew stores in real time, but couldn't resist stopping the camera and single framing while they

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2. The arret is the technique of stopping the live action camera, manipulating the set, and running the camera again. Typically, as in the Edison Studio's <u>Execution of Mary Queen of Scots</u>, the camera is locked off and immobil. [Locate]

advanced their chalk-on-a-blackboard drawings, as in *Humorous Phases of Funny Face* (1907) (fig. 6).

The technique of single frame recording individual and successive ink-on-paper drawings (fig. 8) was pioneered by two newspaper cartoonists who forged a relationship between the daily newspaper and the cinema: Emile Cohl in France (l908) and Windsor McCay in New York (1911). The longer running times of roll media removed the constraint of drawing only cycles; action could commence and continue without returning to its origin. Thus animation evolved from the concept of a phase picture to the concept of a shot, a contiguous piece of action.

Another special effect was the **multiple exposure**, pioneered by Méliès (1902) and others, which involved exposing, rewinding, and then reexposing a single strand of film emulsion. The multiple exposures could superimpose images, create dissolves, and let Méliès act with himself on the screen. Edwin Porter combined multiple exposures with **mattes** to capture a moving exterior outside the window of the station house in *The Great Train Robbery* (1903). Worked with a twist, multiple exposures may also be used to combine animation with live action, as in Edison's *Enchanted Drawing* (1900), which incorporated blackboard chalk scratchons and an actor (fig. 11), possibly shot with a split screen technique. Remember that in these days before optical printers or video compositers the entire image had to be exposed into one original camera negative. **Reverse action**, action that is running backwards, was discovered in 1903.

But it is worth observing that the purpose of the special effect was viewed quite differently by early directors: For Méliès the

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6. Scratchon. Single frame photography of progressive blackboard scratchon drawing is technique used to make J. Stuart Blackton's <u>Humorous Phases of Funny Face</u> in l907. [locate and permission]

8. Single frame photography of successive paper drawings breaks away from cyclic phase drawing and is a pathway to the cel system. In Windsor McCay's <u>Gertie the Trained Dinosaur</u> the entire drawing is recreated for each frame.

11. Split reel technique was probably used in this 1900 short produced by the Edison Company called <u>The Enchanted Drawing</u>. In the action an artist sketches the face of a sad tramp on a paper pad. Next he draws a cigar and the tramp begins to puff large clouds of smoke as the actor leaps back in astonishment. [locate and permission eg in Madsen]

magician it was a vehicle to perform magic, for Porter the storyteller it was a vehicle to advance the **photoplay**, a story told cinematically and incorporating temporal devices, especially cuts which change the point of view, frame close ups, reveal different players' perspectives, and cross cut between parallel temporal action.

Thus by the early 1910s the stage was set—technologicaly (cinema plus processes), dramatically (in the sense of the photoplay), and sociologically (in the sense of the vaudville theatre and audience)—for a cinema industry to evolve. And the special effects and single frame animation studio were now established as part of the film genre within it.

The animation studio and techniques (1910-1920)

During the first half of the 20th century, animation reached maturity. The technique of drawing on paper and photographing the successive individual frames, pioneered independently by Emile Cohl and Windsor McCay, soon evolved into a **cartoon animation** style quite independent of the trick film or live action.

Cohl, among other inovations, delighted audiences with the use of the **metamorphosis**, a shape transformation in which an animated outline magically transitioned from one object to another (fig. 13). Often the two extreme shapes have quite different meanings, and the effect is an alternative to a cut or dissolve. Meanwhile, McCay migrated his *Little Nemo* character from newsprint to the screen (l9ll); and with it came conventions of the newspaper cartoon, such as expression bubbles atop characters—a textbook example of McLuhan's adage of a new medium mimicking an established one. Next McCay brought *Gertie the Trained Dinosaur* (l9l4) to life, the first of a long linage of cartoon animals (again, fig. 8). McCay has said that at first audiences were unaware of the technology and suspected tricks with wires, and that it was not untill he animated a dinosaur—truely a profound creature fresh on the heels of Darwin—that they understood that it was the drawing

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13. Metamorphis is the changing of one shape into another. In computer animation it may be a trivial as inbetweening a polygon in the shape of a keyhole to a polygon the shape of a circle, or as complicated as a fully rendered Buick melting and becomming a river of fire. It is one effect where the computer vastly expands the classical reportroire. The illustration depicts a problem slightly more complicated than trivial because it incorporates lines in addition to the outline. (Drawing by Dick Rauh and Suk-Il Hong.)

that was being made to change. The vadlidity of the anecdote is suspect when one remembers that the public already had been watching animated phase pictures for almost a century; what was novel was the incorporation of the photographic process into animation.

By the early teens, people began to test the idea the animation might make a business—that is that sufficent serindipity existed between the emerging audience and the animator that it was practical to construct a plant capable of mass media fabrication. After all, at 1440 paper drawings per minute, cartoons doen't get finished too often if one person is doing all the drawings.

The first animation studios where founded independently in the early teens by Americans John Bray and Earl Hurd, and by Canadian Raoul Barré. The first technological advances sought to refine the production process and make it quicker, less labor intensive, and more accurate. This entailed the implementation of a few basic procedures that remain with us today as tools of the trade. These include systems for registration, the cell process, the perfection of the animation camera, and rotoscopy. The resulting animation studio mimiced Western fasination with the assembly line and mass production; even in the early l990s it remains a financially viable model. Teamwork, specialization, precision, and information flow constitute a few of its salient features.

Frame to frame registration is important in animation and the solution is simply rigor: register everything—the drawings, the camera, and the film. The first registration systems for drawings used optical **crosshairs** or **bullseyes** drawn on the paper, but this approach was soon superseeded by a mechanical **pegbar** registration system credited to Barre (1914), in which pegs in the drawing table and holes in the drawing paper keep all the drawings in allignment. The drawing paper, then as now, is slightly transparent to faciliate tracing. The system is not perfect—holes wear and ten to lose allignment with repeated repegging, but basically the system works (fig. 15).

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15. Optical registration systems for artwork include bullseyes aka crosshairs (a); mechanical systems include pegbar (b). In the early days each studio made its own pegbar, but by the late 1940s three American standards emerged--the Acme, Signal Corps, and Oxberry, illustrated here. Note that the paper and peg dimensions are slightly different; the hole is narrower (to give the paper a good grip) and slightly wider (to let air pass during pegging). In practice the pegs

The registration of the recording medium—35mm film—is more difficult; remember that the area of a frame of film is is about 70 times smaller than the area of a 12 field cel. The solution requires standardization with strict tolerances so that the **perf holes** (fig. 14) in the film match exactly to mechanical **registration pins** in the camera shuttle (1912). This made the photographed image more steady, elimated weave, and paved the way for more sophsiticated special effects involving multiple exposures, since repeated exposures of one piece of film or composite exposures from many pieces of film would all be alligned. Registration would not become an animation issue again until the era of videotape.

One benefit of registration in the drawing process is to enable individual drawings to be decomposed into static and moving parts which are handled separately. A simple way to do this is to employ **cutouts**, paper drawings laid overtop a background and incrementally moved and photographed (fig. 15.5). The system is

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also have curved tops, as you can see in the schematic (c). (Drawing by Dick Rauh and Suk-Il Hong.)

14. Perforation holes are found in many kinds of roll media including paper tape and movie film. In 35mm film there are two major types: the Bell and Howell perf used in negative and intermediate stocks, and the Kodak Standard perf used in prints that are projected. The difference is that the B&H perf is designed to hold registration whereas the Kodak Standard is optimized for repeated projection at higher speed. Stock is also manufactured in two different pitches, that is the distance from one perfhole to the next. The shorter pictch (.l866") is found in negative stocks, the longer pitch is used for release prints, and is an artifact of how printing machines are threaded. In 16mm film (not shown here) there is only one kind of perfhole. (Illustration by Suk-Il Hong.)

15.5 Cuttouts aka the decoupage system. The moving part of the image (a) is cut out of the whole sheet along the dotted line and laid overtop a static background (b) and photographed (c). Nature performs hidden surface removal. Only that part of the image which moves is redrawn and cut out for each frame. Cutouts are not necessarily attached to pegbar, but if they are free floating they do need some kind of movement guide. Some historians also call what is shown in this drawing the slash system and if you compare it to figure 16 you will observe its only difference is that here the moving action is physically in front of the static. (Drawing by Dick Rauh; the reader is cautioned that his selection of Bette Boop to more efficient because the whole image is not redrawn each frame; furthermore the image is more steady. In practice the cuttout need not be a free floating object, and may be attached to peg holes. It may also be articulated, a technique pioneered by Cohl and Armstrong (1910). In Europe the cutout system remained the preferred method of production as late as the l930s.

Another strategy emerged at the Barré studio called the **slash system**, in which scenes were printed in mass on transcluent paper (1914). The part of the field that contained changing action was "slashed out" with a rasor blade and the paper laid overtop a clean sheet, onto which the changing action was drawn. The pair of drawings was then shot together (fig. 16).

But more important still was the perfection by Earl Hurd of the **cel process** (1915) (fig. 17). The cutout and the slash system reduced work because the entire scene was not redrawn every frame; furthermore the line quality is more stable, since the unchanging lines were the same on each printed sheet. The cel system expands this concept by inking the drawing onto a registered *transparent* cel, opaquing it by painting the backside of the cel, and then layering this cel overtop of a single static background and photographing the stack. The cel process separates foreground and background art into work which gets drawn once and work which gets drawn every frame, and it allows the foreground cel to be translated relative to the background. This requires the invention of a **compound table** onto which the backgrounds and cels are placed for photography and

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illustrate this technology may be placing her into a technology which is before her time.)

16. The slash system (aka the slash and tear system) begins with identical drawings that have been printed onto paper and pegged. Whever action occurs the drawing is torn away (leaving a hole in the paper), laid over top a clean sheet of paper, and the area inside the hole is drawn in. This approach is the opposite of the cutout because the static action is laid on top of the changing element, rather than laying the changing element on top of the background. This setup is useful when the changing element wants to go behind things.

17. The cel system. The background is drawn onto paper and painted; the foreground is drawn onto paper, then trace inked onto one or more flexible transparent cels, backside painted with opaque colors, then laid overtop the background and photographed. Action which is static is draw onto cels or backgrounds which are used for many frames, only the moving parts are transferred to cels which are different for each frame. [color example, plus process diagram].

moved on calibrated scales. It was also possible to move the camera closer or farther away from the table. These new variables were tools of the new animation directors.

The facility of the animation stand to also project images provided a way to convert live action images back into drawings, a process called **rotoscopy**, and attributed to director Max Fleischer (1915) in the midst of trying to figure out how to dramatically increase throughput: simply film actors and 3D objects using live action, and then project the frames one by one, trace 2D outlines of the characters or objects onto individual drawings, and send the drawings down the animation process pipeline. Rotoscopy remains a basic tool today in film and video post-production, especially in situations where mattes cannot be generated automatically from the footage. Rotoscopy is employed whenever animated characters need to realistically interact with live action, as in *Who Framed Roger Rabbit*, and in creating effects like the light swords in *Star Wars* (fig. 23). It is also used to guage the positions of puppets during stop-motion photography, a technique developed by George Pal in 1933.

In addition to the animation camera stand one final piece of filmmaking technology emerged during the teens, completing the basic technology. This was a special effect called the **traveling matte** shot, invented by American Frank Williams (1918). The new trick was accomplished by filming an actor against an all white or black background and then preparing a high contrast matte from this negative which was used to combine, or "matte in" the actor to a new background scene. At first the trick was done entirely with a camera, but in the 1930s was streamlined on the optical printer. After the 1950's the process was worked in color, as well as being adopted to video, first in black and white and then color.

In Europe a wider variety of techniques were explored, especially the use of 2D and **3D articulated puppets**, designed to be moved incrementally and photographed on a frame by frame basis

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23. Rotoscopy. The 2D rotoscoped outline of a live action watch permits the computer animator to visualize where this 3D object will exist in the synthetic landscape. The final computer graphic production will consist of the animated wire frame background minus the tracing, plus a black and clear core matte of the traced watch. These mattes will then be used to combine the CG background with the live action foreground. (Courtesy of Digital Effects.)

in miniture 3D sets (fig. 23.2). The first puppet animated films, such as Ladislas Starewicz's mechanical insects (1911) and Edward Roger's *War in Toyland* (1912), introduced a host of inovations. The basic issue of figure movement is solved with an internal **armature**, a metal skeletal structure with articulated joints that can be moved into various positions, and around which wooden (or in later years rubber or plastic) characters are built. Techniques to change facial expressions including the use of flexiable **facial masks** by Starewicz (fig 23.5), and the idea of **multiple heads** for a finite set of facial expressions—Starewicz is said to have as many as 200 different heads for major characters (fig. 24). Three dimensional computer animation is often simply virtual puppet animation.

By and large the content of this early fare was the cartoon character, already well stablized in the newspaper. It is not surprising therefore that the early evolution of this character was initially dominated by newspapermen. The trickfilm and lightning cartoonists no longer provided leadership, perhaps because the comic strip artists brought with them not only the characters but also the narrative. In fact, the cartoon influences date from before the arrival of the cartoonists; as early as 1906 Porter had adapted Winsor McCay's *Dreams of a Rarebit Fiend.* In New York, Bray's studio motive was a series of *Colonel Heeza Liar* shorts (1913); San Francisco cartoonist Bud Fisher's Mutt and Jeff was adapted to the screen (1913), and in New York Max Fleischer introduced *Ko-Ko the Clown* (1914). Finally, at the end of the decade, Pat Sullivan and Otto Messner created *Felix the Cat* (1919), a character developed

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23.2 Puppet animation. The tradition of animating 3D objects is as old as animating 2D drawings and a major archology of computer animation. Classical puppets often include articulated skeletons, hinged jaws for lip syncing, and facial features which are subjected to variance.
23.5 Facial masks are an early puppet concept easily adapted to computer animation. These vector graphic templates were made by painting lines on an actor's face, and shooting still coplaner photographs of the actor making different expressions. These are then digitized. Because the number of quadralaterials in each mask is the same, the masks may be computationally interpolated or blended to animate from one expression to another. (Courtesy Pierre LaChapel and Philippe Bergerson.)
24. Catagorical sets of body parts, such as replaceable heads and hands, facilitate the work of the puppet animator.

especially for the screen and the industry's first cartoon superhero. Felix the megastar paved the way for a succession of cartoon animals.

The Classical Period (1920-1960)

The most widely known proponent of the cartoon process was a man born after the invention of the cinema, Walt Disney. Disney started out in Kansas City, but by the l920s he had moved to Hollywood and in a few short years technologically and artistically leapfroged the business. Disney encouraged the process of animating by **extremes**, whereby the animator drew only the **key positions**, and the intermediate drawings between the poses were drawn by an assistant, called the inbetweener. The number of **inbetweens** as well as their temporal relation to the two keys was indicated on a **timing diagram**, also prepared by the animator, that accompanied the key drawings (fig. 8.5). Standarization also involved utilization of **model sheets**, **coloring diagrams**, and exposure or **dope sheets**, which dictated to the cameraman what cels were to be placed over what backgrounds on what frames. Dope sheet formalized the relationship between animator and cameraman, and centralized production from an upstream control point. Disney introduced the **storyman**, who wrote the scripts and storyboarded the action, and incorporated the pencil test as routine procedure. The preeminent achievements of the studio begin to get realized in l928, when the synchronized sound cartoon *Steamboat Willie* launched the career of Mickey Mouse.

8.5. Key frames, inbetween and timing diagram. The idea of animating from pose to pose, as opposed to "straight ahead" animation where the animation has no clearly defined extreme positions, has wide ranging effects in animation. In classical cartoon animation it invited specialization of labor, with less skilled labor drawing the inbetweens--the frames in between the extremes. In 3D computer animation the process is the same: the extremes are defined parametrically (eg joint angles), and the computer calculates the inbetweens. In classical animation the temporal relationships of the inbetweens to the keys is specified by a hand drawn timing diagram; in computer animation this is usually done by calculating the ease kinematically. The computational analogy of the straight ahead style is dynamic modeling; details of dynamic and kinematic calculations are detailed in a separate chapter.

The 1930's also saw technological advances in the overall film process that were adopted by Disney: color (l932). and the cartoon feature (1937), stereo sound (1940), and automation of the inking step with xerography (1961). In the end Disney actually built his 3D synthetic environments (the theme parks), and successfully exploited the emerging television business.

Advances in the animation camera stand and optical printer were also made during the 1930's. Early animation stands were homebuilt affairs—Disney used pipe in some of his rigs—and only over time did the features fully evolve. Initially the stands were operated manually with control wheels calibrated in real world inches. The complement of features beyond **pan**, **tilt**, **zoom**, and **traveling pegbar** came to include the **rotating table** and the **pantograph**, a mechanical arm which allowed the cameraman to follow a **motion pathway**, an XY graph that showed both the position and timing of the artwork (fig. 96). Disney built his famous multiplane camera with multiple platins, spaced several inches apart so as to entice the three dimensional feel (l937).

Like the animation stand the first optical printers, like the Acme 103 designed by Linwood Dunn, were completely mechanical. An **optical printer** is much like an animation stand, only instead of photographing artwork it photographs film (fig. 3.3). The development of optical printers in the early 1930s vastly expanded the realm of special effects. First of all, the optical printer increased the precision of matte work, and moved a host of in-camera effects—including the arret, multiple exposure and superimposition, reverse action, fade, and dissolve—from the set to post production. All may be invoked as an afterthought to principle photography, and with much more precision. But more importantly, the optical printer created entirely new effects possibliities, allowing images to be repositioned, enlarged or reduced, or freeze framed.

In the l950s a machinest named John Oxberry motorized and to some extent automated both the stand and the optical printer. On the stand he implemented a follow focus system so that the focal length of the lens was mechanically computed and set as the camera moved closer and further away from the artwork. Manually operated

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3.3 Optical printer. The photographic axis is usually horizontal and the field of view is a film frame. The camera, projector, and aerial heads can each translate in XYZ and may rotate. The aerial image projector is optional and is used when it is necessary to carry a matte roll. (Courtesy Focal Press.)

control wheels were replaced or suplemented with electric motors which were operated from a control pannel. Digital readouts were standarized for all the axes of variance—including a frame counter, the compound positions, and zoom. This instrumentation may be designed to be calibrated in either real inches or virtual ones. (The accuracy of a stand is about .001"). The shutter was also numerically calibrated to faciliated in-camera dissolves and fades. In a mechanical sense Oxberry's dual columns minimized the spurious movements of the camera which contributed to jerking images. Oxberry's motorized optical printer included a second playback shuttle; this allowed mattes to be placed in front of the lens instead of bipacked adjacent to the recording emulsion. Thus when the computer got invented the automation the stand and printer could be easily developed further.

But the thirties cartoon style, with its hard, inked outline and solid color area was not a Disney exclusive. Walter Lantz, Warner Brothers, and MGM all formed studios, and a farm full of cartoon characters was born. This tradition of chase sequences and sight gags is so pervasive that most Americans don't even know that whole other traditions of animation exist.

One form of these is an articulated cuttout, often called a **marionette**, but which in contemporary terms we would call a **2D skeletal animation** system. In physical terms these articulated cutout consisted of shapes (such as the body of a figure) connected together with rotating joints, and were often made of opaque sheet metal and used in silhouette backlit, a technique influenced by shadow theater. Variations in the real world include the use of stained glass, which add color, as well as painted color and toplight. One of the first to popularize this approach was the German Lotte Reiniger, whose signature included rotating the jointed 2D linkages to perform magical metamorphosizations, like two birds becomming a dancing girl in her feature film*The Adventures of Prince Achmed* (1926).

The German school also evolved a style of pure **abstract** animation, which even in the pre-sound days was designed to be synchronized to live music. One of these first music visualization films was Walter Ruttman's *Lightplay Opus I* (1921), other pioneers included Hans Richter, Oskar Fischinger, Fernand Leger, Marcel Duchamp, Paszlo Moholy-Nagy, the Sweed Viking Eggeling, and the New Zealander Len Lye. Like their cartoon counterparts, the abstract filmmakers, particularly Fischinger, migrated to color and sound-on-film during the 1930s. Much of this work is very procedural in design (fig. 26). In America the abstract movement was formalized further by John and James Whitney, who employed mechanical pantographs to control paper cutouts (1944), very much in the linkages tradition of Reiniger. And abstraction will continue to be a theme of the motion graphics school. We develop both of these themes in the sections on Analogue Computer Animation and Motion Graphics/Motion Control.

C2 Eastern European countries lead developments in puppet animation; major works include a feature film by the Russian Aleksander Ptushko called *The New Gulliver* (l934) and a phethoria of work by Checkoslovak Jiri Trnka and others since l949.

The 1930s and 1940s are also a period of experimentation with still other techniques, including directly **drawing on film**, the use of **sand** on glass, the sliced **wax block**, and the **pinscreen** (1934), a gridlike screen of sliding pins which forms (for all practical purposes) a physical pixel memory. The pinscreen is lit from the side so as to cast shadows, and thus luminence is analogical to the physical height of the pin, and thus the length of its shadow. Animated pixel graphics thus also anticipated the computer.

This leaves us at the advent of the computer.

The Origins of the Computer

Analog computers

Computers date from antiquity and they take many forms. What they share in common is that they employ a methodology to solve problems: extract answers from data and to make preductions.

Analogue computers are devices for solving problems that utilize physical quantities capable of continuous change. The physical displacement measures might be distance, rotation, weight, voltages (Wheatstone's bridge is an electrical analog computer), or areas. We are so used to thinking in numbers today that we must remember that analog computers can calculate entirely without numbers by using physical analogs such as eletricity or graphics. Analogue graphical computing devices include the right angle, plumb line, the balance, the compass (all antiquity), the plane table (49BC, modernized after 1620), proportional dividers, parallel rulers, the

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26. Abstract geometric animation. Pioneered in Europe, these frames by Oskar Fischinger from ?? rival the best abstract geometric computer animation and are timeless examples of audio-visual harmony. [locate]

pantograph (1650), as well as the more complicated elliptical trammel (1540), the pantograph to draw parallel curves (1650), the ellipsograph (1790) for drawing ellipses, the volute compass used to draw spirals (1791), and the planimeter (1814) to measure areas. Analog computing instruments may also be calibrated with a numerical scale (fig. 41). Analog scales are found in the circular zodiac (), the astrolabe (900), which evaluates the season and the angle of the sun to determine the time of day, the protractor to measure angles (), William Oughtred's slide rule (1620) to do multiplication, division, logs, and trig.

The technique of harmonic analysis, formulated in 1822 by Jean Fourier also encouraged graphical computing. The **harmonic analysis** theorm states that a complex waveform may be decomposed into a collection of fundamental sine wave frequencies (figure 42). One advantage of harmonic analysis was that if a complex phenomenon could be accurately analyized then it could be predicted. The stage was thus set for three major developments:

The first of these was Englishman William Kelvin's harmonic analyzer (1876), which accepted a purely graphical input, performed a calculation with linkages and dials, and displayed numerical readout (fig. 43). The inverse of this machine, the **harmonic**

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41. Analogue computer examples. A spring scales--the difference in the position of the pointer is analogeous to the difference in the weight of two objects. The slide rule--the difference between two positions on the scale is analageous to the logorithms of the two numbers. The planimeter--the polygonal area, as traced by B, is the distance from A to B times the distance wheel D has rotated. Wheatstone's bridge--an unknown resistance is analagous to balancing it to a known electrical resistance, here about 65 ohms. [to Dick Rauh & Hong].

41. Harmonic analysis is especially useful to analyize functions (waveformes) that incorporate periodic, sineasodial frequencies. For example, hourly observations of the height of the tide reveal a pattern of underlying frequencies: a rapid osillation betwen night and day (caused by Earth's spin), a slower frequency of about one month (caused by the Moon's orbit), and a still longer period (caused by Earth's annual orbit).

41. Harmonic analyizer is equipted with a stylis to trace an input curve. The stylis in turn is connected by linkages to rotating read-out dials inscribed with scales. Kelvin's machine contained 10 read-out dials, each of them depicting the amplitude of a different sinewave frequency, and was therefore able to identify up to 10

synthesizer (1898) used cranked eccentrics and linkages to move a drawing pen. There are a number of variations in this design, including the pendulum harmonograph (1857), used by Lissajous to explore sinewave harmonics (fig. 4-44, 4-44.5), and the harmonic synthesizer (1898), which uses cranked eccentrics and linkages to move a drawing pen (fig. 4-45). In a famous proof, Englishman A.B. Kempe (1857?) proved that any algebraic curve could be described by a linkage, and vice versa, unifying algebra and geometry.

Another analog computer do employ graphics was Charles Boys' **integraph** (1881), which traced one or more input curves, accumulated their variations, and output the results as a composite curve graph. Isographs are similar to the harmonic analyizer except that their output as well as their input is graphical. The culmination of the analog mechanical computer era may well be the motor—powered differential analyzer, built by Vanneuar Bush at MIT (1932). The **differential analyzer** calculated using rotating shafts and gears, and output the results as graphs on paper.

The developments in kinematics after 1822 accelerated a fusion between the study of geometry and the study of objects in motion. Animation lies in the mechanisms of the industrial era—rollers, cams, gears, crank shafts, and linkages.

Like animation, automatic computation also originated during the machine age, and involved applying power—energy—to the computation process. This process can also be applied to digital systems and we will discuss that next, after which we will return to techniques of using analog computers to make animation.

Digital computers

Calculating devices which store and manipulate numbers originated more than 5000 years ago. The most ancient machine, still used today, is the abacus. Another inovation was the use of , geometric shapes (or electronic codes) used to represent numbers. The major advantage of symbols is that you can manipulate the symbols instead of the physical counters. Algorithms—the software of science—also date from antiquity and include methods to multiply, divide, do algebra (1100), equations (1500) like calculating perspective, calculus (1600), and perform analytic geometry ().

Genus at mathematics migrated from Greece to Arabia to Europe, but even Europe's strengths in symbolic manipulations did

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harmonic components of the original wave. One of Kelvin's interests was analyizing tide observations. [assign]

not entirely solve the calculation problem. Calculation requires the actual performance of a procedure with numbers, and not algebric symbols representing numbers. Calculation is a fairly necessary process if one is going to test theories with real data, let alone simulate theories with synthetic data.

Mechanization of the calculation problem began in earnest with the work of Franch mathematician Blaise Pascal, who constructed a mechanical adding machine, the Pascaline, in 1642 (figure 50.10). The Pascaline calculator could add and subtract and automatically carried. Like an abacus it contained one word of memory and was discrete; unlike an abacus it was blatently digital. An improvement by Leibnitz in 1673 faciliated multiplication and division; the addition of a keyboard in 1??? solidified this as a basic office calculator design.

In the 1800s, industralized power technology was applied to the calculating problem. The most famous of these thinkers was Englishman Charles Babbage, who conceptualized the **difference engine** (1822), a mechanical calculator which could perform all four basic arithmatic operations and thus solve simple algebraic equations (figure 50.13). Babbage's more grandose design, the **analytic engine**, conceptualized implementing a conditional transfer (an if) which would choose between two alternate sequences of instructions based upon the result of a comparison between two numbers. Babbage envisioned coding numbers onto the recently invented Jacquard loom punch cards (1804); the analytical engine would read the cards and rotate the counter wheel registers accordingly. Instructions, (eg which register to load the number into, and what arithemetic operations to perform between registers) were also coded on cards and fed to the machine, enabling Babbage's Mill "to weave a sequence of numbers." Unfortunately for Babbage, a Sweed, Pehr Schuetz succeeded in actually constructing a difference

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50.10. Pascaline adding machine. The illustration depicts a six decimal digit long register constructed from wheels and incorporating a cog wheel feed mechanism to effect carries. The algorithm of addition is embeded in the mechanics of the carries, as well as the user, who knows the number to add to the value displayed.

50.13. Multi-register digital calculating machine. The difference engine is also sometimes called a difference mill, reflecting its water power. Numbers representing the input as well as resultant values are stored in the machine as counter wheel registers.

engine first (1854), and an American, Herman Hollerith, would most successfully parley the punch card tabulating machine (fig. 50.14) into an industry (1890). Hollerith got his start tabulating the 1890 census. In 1896 he formed the Tabulating Machine Company to mass produce his technology; in l924 this became a nucleus of the IBM company. And IBM automated the office, selling a line of products built around punch cards—keypunches, card punches, printers, counters, sorters, and eventually, computers.

Mathematical advances were also necessary to advance computing. **Binary numbers**, the quantum of data, were introduced into the West by the Master of Number Bases himself, Napier, in the 1600s. Englishman George Boole found success at developing a symbolic logic of thought (1854). In America Charles Pierce applied boolean logic to electrical switching circuits (1867) and Sheffield demonstrated that all arithmetical functions could be reduced to the single logical function **notand**, the quantum instruction.

If indeed IBM was driving from the side of the punch card then Western Electric, at its Bell Telephone Laboratories, was driving from the side of communications. The Bell work was both theoretical and practical. As early as 1919 telephones began to be equipped with dialers, so that a switching exchange could automatically route a call. But it was not untill the l930s that Claude Shannon coorelated the overall behavior of electrical switching circuits to mathematical logic. In 1937 George Stibitz built an electromechanical relay circuit that performed boolean logic. Next, he combined these circuits to construct first a binary adder, and finally an all-binary number calculator capable of performing all four arithmetic functions. This was demonstrated over long distance telephone lines (1940). Before the end of the 1940's, mechanical relays were replaced with vacuum tubes as with the ENIAC, built by J.P. Eckert and John Mauchly (1945).

The concept of encoding the instructions as binary codes and storing them in the computer's memory along with the numerical data was advanced by Johnny von Neuman (1945) with Alan Turing's knowledge of what is and is not computable (1936). The first stored program computers were built by Maurice Wilkes in Cambridge (1949), and by Mauchly and Eckert, ultimately at Remington Rand (1951), who produced what was really the first computer someone

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50.14. Hollerith tabulating machine counted data recorded on punch cards. Spring loaded pins push againt the card, and where there is a hole the pin penetrates the card and completes an electrical circuit.

could buy—the UNIVAC. IBM followed on quickly, building both decimal (the 600 series) and binary (the 700 series) machines throughout the 1950s as well as inventing much of the support technology: operating systems, assemblers, compilers, theory of computation.

By the late 1950s the transistor (invented in l947 at Bell Labs) began replacing the vacuum tube in computers. Like the tube, the transistor could be used as an analog amplifier as well as a logic switch, and it drastically reducing the size, construction costs, and power requirements, while allowing for faster and more efficient computing. But by mid 1960s transistors were replaced by even denser **integrated circuits** (1959), which laminated the transistor, resistor, capacitor and circuit board together into a single chip with no interconnecting wires, again drastically reducing assembly costs, interference, power and air conditioning requirements, and increasing speed. Light, after all, does travels nine inches a nanosecond. Some of the first applications of chip technology were memory circuits (registers), counters, and entire logical gates.

There is more to this story, but this brings us up to the eve of digital computer animation

IBM employed this low density integrated circuitry in its System 360 (1964), a new single architecture which fused both its decimal and binary representations into its native instruction set. One of its main features what that the design was not a single piece of hardware, but rather a system architecture which consisted of an instruction set and programs which could be implemented on a gradient of hardware with increasing price and performance, allowing migration of the computing task as it grew larger (fig. 50-22). It could address an unheard of 16 mbytes of memory and had a

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50-22. A computer system incorporates the concept of software--either at the assembly language or high level language level--which can be migrated onto a range of different machines and peripherals. The machines may be newer hardware which incorporate significant technological inovations, hardware which executes instructions slower or faster, or hardware from different manufacturers. Pragmatically speaking, in addition to a basic series of instructions, a system also includes capabilities for managing code, loading it into memory, performing I/O, and handling problems when programs go amok.

32 bit word. One of its options was the **2250**, an interactive graphics display which supported a light pen. IBM was very careful to design the **360** so it could be **upward compatable**, that is newer versions of the machine could support additional instructions, yet the primitive instruction definitions remain constant. And indeed modules compiled on a **360** will execute on today's very latest IBM **30XX** machines.

Alternatives to the mainframe began to emerge in the early 1960s. In 1959 Digital Equiptment Corp (DEC) introduced the PDP8, an early minicomputer. But the baseline driving the technology was the density of components in a single integrated circuit, and this continued to increase. Intel Corporation succeeded in manufacturing a single chip containing 1 kbits of memory (1970), a 4 bit ALU (1971), and finally an entire **microprocessor**—a single chip containing an 8 bit ALU, memory, and I/O control (1974). Intel assumed the market for its microprocessor chip—the **8008**—would consist of replacement systems for applications like smart elevator controllers. (After all, why construct mechanical switching logic when you can simulate it on a computer—furthermore a computer can be reprogrammed, to change what floors an elevator stops at, add new floors, or service calls in a different manner.) But unexpectedly a hobbyist movement exploded: boy scouts, ham radiofiles, and artists began building computer systems themselves. After all, the microprocessor was a complete computer.

The breakthrough came in 1975, when Edward Robert's Micro Instruction and Telemetry Systems Company (MITS) introduced the Altair 8800, a computer kit. In its initial version the machine had no keyboard, no alphanumeric display and was programmed by toggle switches on the front pannel, with the results displayed as status lights. Memory was 256 bytes. Within months however its S-100 bus would emerge as an early standard, and software handlers for a keyboard and monitor were written, as was a loader, assembler and file system. Before the end of the year students Paul Allen and Bill Gates created a **BASIC** Interpreter, and a company called Digital Research created **CP/M**, an OS for the machine. Byte magazine was born in 1976 and in 1977 a young Steve Jobs and Michael Wozniak succeeded in designing and manufacturing an entirely stand-along personal computer system that was already assembled—the Apple. The **Apple Computer** included a backplane, the new **6502** microprocessor, 48 kbytes of memory, a keyboard, color TV display, and casette or floppy disc peripherals. The personal computer had arrived. In 1979 Motorola introduced the **68000**, a 16 bit word microprocessor, and in 1981 IBM legitimized the PC by introducing their own, built around the Intel **8086**. And the rest, as they say, is history.

This brings us to the beginning of our story.

Analog Computer Animation

During the 1950's and 1960's artists and scientists explored both and digital computers as a way to make moving picture imagery. The **analog computer animation** tradition includes both electronic as well as mechanical approaches. The mechanical approaches to drawing have been explained above and can involve linkages and mechanical assemblies. The electronic approaches involve creating changing images using continuously varying voltages.

Electronic Analog Computer Animation

The foundation of the electronic school was the modulated cathode ray tube (CRT), perfected in 19xx. Animation is achieved by using oscillators and variable resistances to position the X and Y deflection coils of the oscilloscope and to vary the intensity of the beam. Here, essentially, was an **electronic harmonogram** in which modulating electronics substituted for mechanics. The quickly written image that appears on the face of the tube was termed by pioneer Ben Laposky as an **oscillogram**. Other pioneers in the 1950s included Mary Ellen Bute and Hy Hirsh, who played these instruments in real time controlling them with dials and patch cords. These artists were aware of both the kinetic aspect of their work as well as its static possibilities, photographing the screen with both moving and still cameras, and occasionally using filters to achieve color (fig. 46).

The fusion of the electronic harmograph and television is the **video synthesizer**, a performance instrument able to be played in real time using a keyboard, switches, and dials. The first commercially successful analog video synthesizer was Lee Harrison's *Scanimate* (1970), commercialized by Computer Image Corp in Denver. [into caption: Artwork for the Scanimate consisted

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46. Oscillon 254 by Ben F. Laposky, 1957. This analog electronic harmonogram is made by controlling the voltage, current, frequency, phase, and waveforms that modulate the X and Y deflection coils and beam intensity of a CRT. (Courtesy Ben F. Laposky.)

of clear core high contrast kodalith cels mounted on pegbar and backlit. A high resolution (1000 line) television camera captured this image and displayed it on a corresponding high resolution monitor where it be manipulated by the computer animator. The high resolution monitor was **rescanned** by a standard NTSC or PAL black and white camera, that is, the television camera was simply pointed at the high resolution screen and captured the image on it. Finally, the black and white video signal was quantized into five grey levels and colorized.] (fig. 47).

"Programming" the Scanimate involved neither keyboard, menu, nor language, but was accomplished by connecting the various modules together with patch cords. The high resolution display monitor was equipped with special deflection coils driven by a variety of oscillators, summing amps, multipliers, biases and other analog modules which twisted the monitor's raster electronics so that the image could literally be tied into knots. Basic source modules produced waveforms included sinewaves, sawtooth, square wave, and trangulars. Pulses could be generated of arbitrary frequency and duration. Temporal control—that is how the raster breathed—was provided by independent analog ramps which defined starting and end voltages and duration times; these were patched into the oscillators et al to control them.

Throughout the 1970s Harrison's CIC functioned both as a media producer and an equipment manufacturer. CIC's first commercial clients arrived in the late 1960's. [and add in example from Filmography.] Noteable artistic work included the films *Growing* (1970), and *Scape-mates*, made in 1972 by Ed Emshwiller (fig. 48). In the production industry Scanimate became part of the emerging video production industry; major production houses who installed Scanimate included Dolphin Productions in New York, Image West in Los Angeles, Far East in Tokyo, and RTL in Luxemberg.

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47. Video synthesizer block diagram. Backlit artwork is scanned by high resolution camera and displayed on hirez black and white monitor. The deflection controls, greatly simplified in the drawing, control special deflection yokes in the monitor. The hirez monitor is in turn rescanned by an ordinary television camera, routed thru a colorizer, and recorded. An alternate input is black and white video to the hirez monitor. [illustration in hypercard; consists of two cards].

48. Analog computer animation. These frames from Scape-mates by Ed Emshwiller were made on a Scanimate machine and demonstrate its potential for rich organic form. [locate]

Scanimate may be the first widely used video imaging device that does not emulate a preexistant film technique and the first moving picture product to be successfully market as "computer animation."

[move] One thing the new houses had to do (DEI, III, Magi, Able) was to distinguish themselves from Scanimate, which was also "computer animation." The difference was that they were digital.

In the early 1970s the concept of a video artist specializing in synthetic image (often synchronized to music) became a reality for many people. Some, like director Ron Hays, employed a variety of systems to formulate work. Many others resorted to building their own video synthesizers, both to process preexistent video imagery as well to generate totally abstract imagery (fig. 49). Strategies included magnets (by video art pioneer Nam June Paik), colorizers and feedback devices (Paik and Shuya Abe, Dan Sandin), rescan (Steve Rutt and Bill Etra), and digital approaches (by Steven Beck, Eric Segal, the Vasulkas, Tom Dewitt, Vibeke Sorensen, and Carl Geiger). These digital video art approaches varied widely, from digital controls of key parameters to special purpose logic circuits designed to manipulate the video signal.

Forays by Lee Harrison to advance the video synthesizer into the realm of an electronic cel style technology resulted in CIC's *Caesar* and *System IV* (1975), but the approach never emerged as a popular technology, probably because by this time it was easier to employ the more general purpose digital computer and frame buffer for the task. But it was not until the late 1980's that the last of the Scanimates would stop operating, effectively ending an era.

Mechanical Analog Computer Animation

The use of mechanical systems to make computer animation are closely allied to a cinema form called **motion graphics**. The development in motion graphics occured during the 1960s when experimental filmmakers began using repeatable equipment to construct sequences of abstract images. The brothers John and James Whitney Brothers employed mechanical gunnery clockwork which rotated small backlit metal patterns, which were gelled to give color. These in turn were photographed in multiple exposure to produce producing kalidoscopic effects. Using this "analog

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49. Video synthesis. The real time artform of playing a video synthesizer. A delux unit should include rescan, video feedback, colorization, video inputs, audio frequency inputs, waveform generators, plus all the digital futures. This pictures by ?? is made ??. [fill hole color]

computer," the Whitney films, like John's *Catalogue* (1961) and James's, *Lapis* (1963) represent a center position between the older abstract animators like Fishinger (sp?), and the still-to-emerge computerization (fig. 52).

Another pioneer from this analog yet automated era is Doug Trumbull, largely responsible for introducing, in the movie *2001* (1968), a time lapse exposure technique called **slit-scan** in which light is smeared onto the individual frames of film (fig. 53).

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52. Analog computer animation. This image is made by successive rotation and multiple exposure of a single template, successive images are formed by local rotations and translations to the template itself. Color is via table lookup. From a descriptive point of view it is immaterial if the imaging aparatus is analogue with physical templates or digital with virtual templates.

53. Slit scan technique makes use of narrow line (the slit) which travels across the artwork or the recording medium (the scan) while the exposure is made. Physically the slit is actually a narrow opening cut into a piece of very thin metal. The regular camera shutter remains open while the slit is in motion, although it is closed while the film is advanced.

In effect the slit functions like a focal plane shutter. If the camera and artwork (or prop) is held steady during the exposure scan then the newly recorded image looks normal and undistorted. But if the camera and/or the artwork is moving during the scan, something magical occures. For example, if the slit is a horizontal line progressing from the bottom of the screen to the top (A1), and the camera moves closer to the image while this is happening, then the resultanting image appears in tilted perspective, closer to the viewer at the top of the screen (A2). The direction arrows superimposed throughout this figure indicate the direction and travel of the slit (in A1 this is the up arrow) and the effect of the camera zooming on the artwork (the two arrows from the larger rectangle to the smaller one) during the exposure of a single frame.

The generation of successive frames requires changing a parameter on a frame by basis. For example, if the start position of the artwork is translated vertically (B1), while repeating the identical slit scan and zoom camera action employed for the first frame, the resultant image will seem to animate along the plane of the tilted perspective (B2). A program for this might look like:

```
Set initial position of artwork
Repeat frames =  1 to 100
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```
    Translate artwork up some small constant amount
    Position slit at bottom of frame
    Position camera to zoomed out position
    Open the real camera shutter
    Repeat slitincrements = 1 to 1000
       Translate slit up 1/1000 of frameheight
       Zoom camera in 1/1000 of zoomdistance
    End repeat
    Close the real camera shutter
    Frame advance
End repeat
```

Variation in the slit scan process include changing the thickness of the line (a wider line produces a softer, less sharply focused image); the geometry of the line (C); the movement of the line (direction and speed); even animating the line's geometry on a frame by frame basis. And obviously the camera can pan and rotate as well as zoom. More of these parameters can change on a frame by frame basis too, so the range of effects is quite large.

For example, given a live action scene (D1), if the slit starting position and camera zoom distance are held constant (D2), then the result will be alive action scene with (consistant) forced perspective (D3). Or, given an unchanging grid (E1) and consistant zoom (E2), animation of the slit from a straight line to a circle (E2) will caluse the resultant image to progress from a flat plane in perspective to a tunnel (E3). In (F1) the image and slit are constant but the amount of camera zoom changes on a frame by frame basis. The result is an image changing from deep perspective to one parallel to the image plane.

Do recognize that with most physical systems both the slit and the camera zoom are moving continuously, and that the program example above is a discrete approximation. Assuming the resolution is fine enough such a strategy does work, although it is prone to aliasing. To simulate slit scan techniques entirely in a digital domain the input image must be digitized and the slit though of as a window projected onto a narrow strip of the resultant image. Most of the time a better approach would be to simply determine the mapping from the input image to the result and calculate the result parametrically.

Slit scan techniques are slow because the time to move the camera and artwork during each frame is measured in minutes. The computer's role in this automation include not only reducto tedium, Whether or not the machinery is computer controlled, slit-scans require that a scripted, notational plan be prepared in advance of shooting. Equally algorithmic was the work of Canadian pioneer Norman McLaren, who employed the **strobe**, a multiple pass optical technique, in the short film *Pas de Deux* (1969). [to chronology or loose as did the Australians Arthur and Corria Cantrill, who employed it in color in the films *Heat Shimmer* and *Waterfall* (date ??).] On an animation stand a strobe is made by multiple exposures of static artwork with the camera moved closer (or further away) from the artwork, and it is similar to a **streak**, which is made with the camera zooming with the shutter open (fig. 54).

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but an ability to think about the process more strategicly. (Illustration courtesy Dick Rauh.)

54. Streaks and strobes. A strobe and a streak are similar except a strobe is discrete and a streak is continuous. A streak effect is achieved by leaving the camera shutter open while the artwork (or camera) is in movement. A strobe effect is achived by moving the artwork (or camera) and making multiple exposures on a single frame of film. The critical difference between a streak and a slit scan is that there is no moving slit in the streak (or strobe) process.

A streak animates by changing initial and terminal artwork (or camera) positions on a frame by frame basis. In the illustration the word SALE is streaked progressively longer distances from frames 1 to 10--the starting position is held constant in an initial position just below the frame, and on each successive frame the leading edge of the streak, or the head, is streaked progressively further from the initial position. The action is that the word SALE animates up into position in 10 frames (A). The apparent 3D curve is simply an artifact of the camera move. To collapse the tail of the streak, say from frames 10 to 15, the ending point of the streak is held static, but the starting point of the streak is animated upward, so that the tails gets progressively shorter until only the word SALE remains on the screen. Diagram B shows the distance of camera travel for each frame; Diagram C is layout notation for the same effect.

A strobe animates much the same way as a streak, only instead of moving the artwork (or camera) with the shutter open during the frame, the artwork (or camera) is moved in a series of discrete steps and shot with multiple exposures on a single frame (G and H). A strobe of live action footage is achieved by rephotographing the original action as a series of multiple exposures, while changing the sync in the temporal domain (I and J). The effect is that the live action movement appears to expand and contract. In order for the

Popularized by companies like Robert Able Associates, Image Factory, Zepplin and CelArt, motion control techniques became immensely popular during the 1970s, and became the foundation for a new look in television graphics (fig. 56). The motion control techniques advanced the conplexity of procedural, notational image creation script. The new art was still written on exposure sheets, but in these applications the notational domain is vastly expanded to control the sculpting of images using light. Computerization of these processes was inevitable, but by the 1980's both the technique and the style had been almost completely replaced by synthetically generating the images.

Computerizating the Animation Stand and Optical Printer

[Before we turn our full attention to the computerization of the visual itself, let us dwell on just how computers are interfaced to classical animation stands and camera rigs, and perhaps more importantly, just what new benefits the first generation of computer animators discovered. They are important because they are still benefits, although less obvious and more taken for granted now. It is somewhat ironic that these events occurred in parallel with the first all digital movies.]

Computerizing the animation stand was simple and requires computer controlled electric rotary motor. Motor powered cameras replaced hand cranking as early as 1909; by the 1930's the electric

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tail of the strobe to catch up with the beginning it is necessary to for the live action to stop moving at some point. Depending upon the speed of the original action, the strobe's effectiveness varies with the closeness of the increment chose, i.e., the faster the screen action the smaller the increment between the multiple exposures. The multiple exposures must be in constant relationship, such as every other frame, or every forth frame.

Streaks and strobes require careful planning and testing. Neither technique works with white titles or art, since they burn out the image, and black is usually a preferred background. When shooting artwork it is also best to matte the head image, avoiding the contamination of a double exposure. Color may be introduced in a variety of ways, but the most typical to backlight the artwork and use gels.

56. Motion graphics production usually begins with rather simple clear core kodalith artwork which is pegged on a light box, covered with a colored jel, and photographed a la strobe, streak, or slit scan technique.

motor had penetrated all facets of the movie studio, including camera heads, props, animation stands, optical printers, and ??this true motion control systems.

The first computerized animation stands and optical printers were built by John Oxberry, a manufacturer of animation stands and optical benches, and the Atlanta company Cinetron (196?), a startup business. Oxberry's first computerized stands used a DEC PDP-8 computer, Cinetron adopted the Hewlett Packard ????. In a minimal system (fig. 4-55.5), a computer and terminal are attached to an animation stand consisting of a compound table and zoom column such as was illustrated in fig. 4-22. For an optical printer the computerized parameters are the same as those shown in fig. 4-3.3. Initially most systems were equipted with paper tape I/O and had no on-line magnetic media; today a floppy disc drive is standard.

The computerization of the stand brings all of its degrees of freedom under formal command-control. These include table X and Y translation, table rotation, the movement of both pegbars, camera vertical movement, frame advance/reverse, and shutter angle. Readouts on the stand, whether they are physical veeder scales or electronic number displays, correspond to the coordinate system of the commands entered by the operator via the keyboard. Such a system may also be used in input mode by positioning the peg bars, compounds, and camera and capturing all the counter values into computer memory. The operation of the camera and the positioning of the components may also be done manually using hand cranks or via the computer using a joystick.

To photograph a sequence the operator composes a series of commands, possibly incorporating some of these saved data positions, which the computer interprets and outputs as a sequence of stepping increments which are sent down the bus to an I/O port where they are translated into electrical pulses which turn the motors and shoot the sequence of frames. In fact the actions may even be previewed before actually shooting film.

Benefits of Computer Animation Stand

The computerization of simple animation and optical effects equipment expanded the productivity of the cameraman. One one hand it made the job easier. Human error was still a factor, only

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55.5 Computer controlled animation stand. Commands entered on the keyboard and displayed on the screen orchestrate stepping motors on the stand to replicate the actions of the cameraman.

now once the cause of a flaw was discovered it could be repaired without another error slipping in somewhere else during the reshoot. But on the other hand the job became more complicated, because the sequences of action themselves became more complicated. One could shoot tests easier, encouraging more previewing and fine tuning. Moves which would before would have been troublesome or impractable were now the orders of the day.

Above and beyond automating the animation stand or camera rig it quickly became obvious that the computer conferred some new and unique benefits to the animation process. One of these benefits was that a new kind of scripting language emerged which addressed the photographic process as a series of linear commands, rather than the spread sheet style of the exposure sheet. Because we discuss languages in more detail later, we defer further development of this topic here.

Another immediate benefit was that the computer could perform calculations, particularly eases, fades, and dissolves. Motions could now be defined only by their extreme positions, and the CPU could calculate the intermediate positions for pans, tilts, rotations, zooms, and traveling pegbar, and position the mechanics accordingly. Fades of any length (and not only the classically prefigured lengths) became trivial because of the precise shutter control.

Precise shuttle control (frame advance) made skip framing, double frames, and holds easier. The filming of cyclic action became simplified because the computer could quickly and reliably open and close the shutter in coordination with frame advance. For example an eight cell cycle could be filmed with only eight cel changes—the computer simply ordered the first cel mounted and shot every eighth frame, then rewound the camera and ordered the second cel mounted. This reduced handling dramatically and extended cel life.

The use of a computerized animation stand in input mode, that is to site thru the camera viewfinder or project a field guide and then capturing the numerical positions of N-S, E-W, and zoom into memory, provided an ability to digitize **control points**, camera and table positions that are obtained empirically. This provided the fielding director an alternative to keyboarding positions. After a series of control points is captured the computer may be instructed to move from one to another according to some (easing) rule in some number of frames. Or, the compound table might be instructed to move from one fielding to another along the path of an arc. A variant idea is to assign frame times to a sequence of control points and construct a spline through them. Or a freehand path may be drawn, smoothed and followed—sort of the digital equivalent of the mechanical panograph follower. It is significant to note that control points can be edited, that new control points can be merged in and existing control points removed; timings may also be edited.

Analytical checks may be performed to see if panning rates will produce strobe effects; if so the computer can send back a suggestion to change speed. Boundary conditions may also be verified, and actions like trying to move the camera through the floor are restrained. In motion control rigs the software should also alert the cameraman when the camera is including the rig in the photograph or trying to take pictures when its mounts are in the way. The polite system also warns the cameraman if the shutter is closed or if the camera is set to shoot backwards.

Motion Control

Motion Control is the extention of motion graphics into the third dimension and is the repeatable control of real cameras and props, this involves notating positions as well as recording actions generated in the real world. The first motion control systems employed analog electronics and were built by Olin Dupy at MGM (1949). During live action photography Dupy's "repeater head" recorded pans as signal amplifications on a phonograph disc. To replay the action, for example to rephotograph a matte painting, the disc was played back and the recorded signals were amplified to drive a pan motor in the head, so that the camera moved the same as it moved originally (fig. 4-51). If you want to record pan and tilt, think stereo. And if you want to record camera pan and tilt, focus, shutter angle, dolly movement, or even the consecutive angles of a jim arm or crane, then think in terms of a multi-track recorder.

Computerization of equipment to photograph props and models is more complicated than computerization of equipment to photograph artwork. The first multi-axes camera and compound table rigs (fig 57.5) were built in California by Trumbull, along with John Dykstra. The effect of this revolution was an expanding visual

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51. The repeater head and the Dupy Duplicator. In the analog domain camera movements are sensed by electrical shaft encoders attached to a geared head, and changes in the position of the head produce changes in voltage. The fluctuations can be recorded analogicly. Temporal synchronization between the recording and the camera is achieved mechanically with the common drive motor. Playback is accomplished by simple amplification.

vocabulary for model photography (fig. 57), evidenced in movies like *Star Wars* (1977), sometimes with very small f-stops and long exposure times to deepen depth of field. Computerization was also extended to the full input/output model, a la the Dupy Duplicator, and seen in the multi-pass registration composites of *Close Encounters of a Third Kind* (1977). At Robert Able's, Bill Kovacks pioneered the concept of using interactive vector graphics to preview motion control shots, a concept he extended to his Wavefront software. In the best of these systems camera moves can be obtained from the real world or synthesized, and in either case the actions can be edited and smoothed both geometrically and temporally. One sucessful vendor was Elicon, who sold turnkey systems that included the camera on a boom, a computer, and a scripting language.

Finally, note that because a motion control system may permit exposures to be made while the camera and/or artwork (prop) is moving, that motion blur (aka temporial anti-aliasing) may be introduced into shots. Streak photography falls into this category, so do video animation stands that move the camera and table in real time, avoiding single frame recording and creating natural motion blur. When models rather than artwork are photographed this way the process is sometimes referred to as **go motion** or **totalized animation**, a term introduced in 1951 when the process was first utilized. Shooting stop motion footage with motion blur is particularly tricky if you must composite elements together, and require the use of a compositing system able to perform variable density mattes, such as the Ultimat or a digital alpha channel.

Obviously this technology can extend beyond cameras and compound tables to articulated physical models. For a more extreme case think of a human in a body digitizing suit and a robot

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57. Multiple pass photography of models and minitures is used both to record multiple exposures onto a single negative as well as record multiple in-regiestration negatives, for example of a model (onto color negative) and its matte (onto hicon). Multiple exposures onto a single negative might be used first to record the exterior of a traveling spacecraft model and subsequently to record its running lights, which requires different lighting and f-stops. Shooting a matte of the model might be done by lighting only the background to white. A background is shot onto a third piece of original material. A negative matte is prepared; and the background plate is composited with the black core and the space ship with its running lights is composited with the clear core.

programmed to follow the actions, such as walking, running, or spray painting. This is part of the promise of virtual reality.

Benefits of Computerized Motion Control

The introduction of a programming computer into the motion control complex accomplishes the same benefits as computerizing the animation stand: Analog recording media are replaced by digital ones. And the computer interface to the electric motor/shaft encoder commits one to programistic control. And herein lies an allegiance with the work of 3D graphics, CAD/CAM, robotics, and virtual reality. Aside from the repeatability and automation factors, the user may now direct the camera in terms of a **language** that describes the camera in a real-world manner and with real world terms. Another new advantage is that actions of the system, captured by the input mechanism and recorded, may now not only be played back, they may be edited also. It is also possible to elude either the input or output side of the full motion control model. For example one might employ a virtual camera and props to plan moves, and then use the motion control system to execute those moves with a real camera and props. Conversely, one might capture the parameters of a real camera move, and use those parameters to move a virtual camera. This is why the motion control paradigm is such a general purpose design (fig. 55).

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55. Motion control paradigm crystalizes a general purpose input/record/process/replay/output model. The example depicts a camera with two degrees of freedom, pan and tilt, along with a prop to be photographed. During live action photography two shaft encoders transmit these angular variations to the CPU, which records them. In the diagram the two tracks are displayed on the computer's CRT display, along with the images seen by the camera. During replay these angular variations are dispatched back to stepping motors which pan and tilt the head, following the movements made during the live action as exactly as possible (or following whatever movements the animator gives them). In practice the shooting camera and the replay camera may be identical or different. The computer system may also be equipted with a virtual camera and prop, the dimensions and linkages of which are identical to the real camera, this synthetic environment is show at the top, and the view of the synthetic camera is show on the right of the CRT display. A key idea is that both the real camera and the virtual camera are controlled and notationally mediated by a common, identical computer graphic language, and that the

Synthetic Imagery

Computer hardware fusions

We now turn our attentions toward the evolution of animation based on synthetic imaging. In the beginning this was done with one of three technologies: the batch computer and the mechanical plotter, the batch computer and the CRT film recorder, or the the interactive refresh CRT. It was no until the 1980's that video became a viable method.

The interactive cathode ray tube display

Given the classical experiments with mechanical Lissajous figure drawing machines and the development of analog CRT oscilloscope graphics the connection of a CRT to a computer was a logical step for the pioneers. The first computer driven CRT seems to have been the Whirlwind I, built at MIT (1950), and which could display solutions to differential equations. One of the first computer animators, Dr. Ed Zajak of Bell Labs, wrote in 1968 that films were "known to have been made" on this machine in 1951, probably by filming real time off the face of the CRT, there is no surviving evidence that it was used to make animated films. [Well no, probably in the Computer Museum.]

Computer driven CRTs were central to the purpose and design of the USAF SAGE computers built by IBM between 1952 and 1956. In these applications a computer was used to integrate real time radar data from remote site locations and then position blips on the screen to correspond to the position of aircraft. Data about the aircraft's position was stored on a rotating magnetic drum which constrained the display list of all aircraft blips in a sector of airspace. The memory also contained attributes about the blip, or more precisely, about the aircraft, such as estimations of airspeed and fuel—the result of calculations between successive positions. Operators queried information about the blips using a light pen. The attribute data was displayed as alphanumeric text, and vector

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recording, editing (if any) of moves, and replaying of action is all relative to this script. At this level there is no difference to the animator whether the source of the script is real or synthetic, whether the output camera is real or synthetic, or whether source and the output are the same (real-real or synthetic-synthetic) or different (real-synthetic or synthetic-real).

graphics overlays included maps (fig. 61). Less than a dozen of these systems kept track of all North American airspace. In a sense, SAGE was a computer mediated radar system, and as such it abstracted the process further, made the system smarter, augmented it with an information management capability, and distancing the operator from the physical radar sites, which were over 1000 miles to the north.

Although the SAGE machine could be programmed to perform interactive graphics—popping a bikini top off of a wiggling vector graphics hula dancer by clicking on it with a light pen was one of its tricks—it remained for a young MIT doctoral candidate named Ivan Sutherland to develop the concept of interactive graphics as an end in itself. Sutherland's work was done on a homebuilt computer at MIT's Lincoln Lab called the TX-2, which was equipped with an interactive display tube. Sutherland's graphics system, called *Sketchpad*, was an interactive, improvisational design tool for the creation, manipulation, and display of geometric objects in two or three dimensional space. *Sketchpad* had the ability to sketch with a light pen on the face of the CRT; to copy, translate, and scale objects; and to use geometric constraints to square up corners (1963). User semantics included both a drag as well as pick capability and actions were controlled by selecting choices on textual menus displayed on the screen, and by manipulating the object directly.

In terms of animation, it would be more correct to say that *Sketchpad* was an interactive design system, capable of real time display. "Animation" could be made by filming the screen in real time as demonstrated by Sutherland and Steven Coons, in *The Sketchpad Movie* (1963). Coons was one of Sutherland's dissertation advisors and an even earlier visionary who forsaw computer graphics as a design tool and is famous for developing the mathematics to describe generalized surface patches.

The mechanical plotter

Besides making possible the computerized animation stand, sophisticated motion control systems, and CADCAM, the fusion between the computer and the electric motor also resulted in a mechanical drawing machine. Graphical plotters predate digital computers, ranging from devices like the Kelvin tide predictor

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61. Picture from a SAGE machine shows the outline of the United States, coverage zones for different radars, and textual information at certain locations.

(1876) and Bush's differential analyzer (1932) to units where motors independently controlled the movements of a pen in an X and Y axes drawing maching—sort of a motor powered etch-a-sketch.

One of the first companies to manufacture computer controlled plotters was Calcomp, founded in 1959. And one of the first places they were used was in the aircraft industry. In the early 1960s a Boeing group, lead by William Fetter, began using a Mosley plotter to verify templates of airplane parts. Soon aircraft, airports, and human pilots were being modeled in the computer. Fetter implemented a three dimensional perspective program on an IBM-7090 computer and they began to draw sequences of frames, first together onto a single sheet of paper a la a Marey chronophotograph, then onto separate sheets which could be filmed one sheet at a time on an animation stand (fig. 4-60). These very early animated movies showed airplanes landing on an aircraft carrier from multiple points of view including the pilots point of view, views from the carrier looking at the airplane, and wise shots showing the aircraft from the side. Fetter is probably the first to model and animate the human figure; his *Second Man* (1962) was used in a study of cockpit design (4-60b). Fetter's goal from the beginning included animated perspective drawings and in 19?? he was issued a patent for the process.

By modern standards, the idea of photographing paper plots seems a bit primitive, but the bottom line is that it still works and is a technique still employed in a variety of permutations. These include plotting onto paper and shooting it directly, plotting onto paper and shooting it onto a hicon negative (producing clear lines on a black field) which is optically rephotographed with color being added with gels, and plotting onto cel stock and opaquing the cel by hand before photography. An alternative approach is to replace the pen in the plotter with a small light and photograph the plotter from above, keeping the shutter open while the entire frame is "plotted," sort of a poor man's CRT. Again, color is easily introduced with filters.

There remains a key difference between a computer controlling a stepping motor on an animation stand and a computer controlling a stepping motor on a plotter however. In the former case, the intent centers around manipulating a piece of photographic equipment, in the latter case the intent focuses on a simulation of drawing. One may argue, of course, that the compound table of the animation stand is simply an XY plotter in its own right, and that equipt with an opaque disc with a tiny, backlit hole in it, that it can plot out vector graphics just as well as a plotter can. But in order to do this practically one must change their intent—the computerized stand is no longer thought about as a machine to photograph artwork but as a line drawing machine. Changing the intent involves changing the descriptive language of the system, that is, changing the software. And this represents a major evolution.

Film recorder CRT's

Although IBM provided a a point addressable CRT as an output option for their 704 computer (1956), the real breakthrough for computer animation was the introduction, by Stromberg Carlson Corporation, of the SC-4020, an offline microfilm recorder (1963). The SC-4020 included a magnetic tape drive, an instruction set with vector as well as character capabilities, an addressable screen resolution of 1024 square, and a camera, which could be a motion picture camera (fig. 4-64.5). SD4020's were purchased by MIT's Lincoln Labs, Bell Labs, Brooklyn Polytech, and others.

One of the first SC-4020's was purchased by Bell Telephone Laboratories at Murray Hill, New Jersey, and it helped transform Bell Labs into one of the centers for early computer animation. The first computer animated film at Bell was made by Edward Zajac and titled *Simulation of a Two Gyro, Gravity Gradient Attitude Control System* (1963). The action depicts a wire frame earth satellite in orbit and shows how the satellite orientation (attitude) changes according to a mathematical model of the gravity of Earth (fig. 4-65). Zajac programmed the film in FORTRAN, computed it on an IBM-7090 and output to the SC-4020. It is perhaps the first example of a scientific visualization, where an animated graphic visualization displays the solution to an experiment. It was an instant success.

The first pixel animations

The vector graphic drawing of the plotter or the interactive CRT convincingly simulated pen and ink mechanical drawing, but what about continuous tone images, like cartoon cels or photographs, where the image is represented with pixels? It is significant to

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65. Simulation of a Two Gyro Gravity Gradient Attitude Control System includes dynamic modeling, a perspective camera, and a clock. A box representing an earth satellite changes orientation (attitude) according a mathematical model of the gravity of the Earth. See also Fig. 82. [Hunt see Halas and Manvelle, Bell, Zajac in New Scientist 10 Feb 66 or Zajac in Rosebush History or Zajac l964.]

note that pixels were a well established concept long before computer graphics. Digital imaging was used in the Bartlane Transatlantic cable (19--) and were understood by the makers of the iconoscope TV capture tube (19--). Digital pixel image enhancement was applied by NASA to TV pictures from the Ranger Moon Probe (1959) [check],

Ken Knowlton and others at Bell tackeled the problem, both for still and moving pictures. Knowlton's approach was to develop an animation language called BEFLICKS, which permitted the creation and modification of grey scale pixel images. The SC-4020 drew only vectors and did not have a variable intensity, but by drawing very short vectors it could approximate dots. Knowlton then used his language to make his first movie, *A Computer Technique for the Production of Animated Movies* (1964) to instruct in its us (fig. 66). During the next three years Knowlton worked with filmmaker Stanley Vanderbeek to generate a series of experimental animated films, titled *POEMFIELD 1* thru *8* and *Man and His World*, which was exhibited at Expo '67 in Montreal (fig. 67). These first pixel (as opposed to vector) animations demonstrate how purely algorithmic manipulations of the image plane can make abstract film. They were computed on an IBM-7094, shot on an SC-4020, and are one of the first computer animation films to be optically colored. Much of BEFLICKS's design would be incorporated into Knowlton's subsequent EXPLOR language (1970), and his continued collaborations with artists would include Lillian Schwartz and Lou Katz.

Ken Knowlton also worked with fellow Bell Labbers Leon Harmon and Manfred Schroeder to employ halftoning methods, so that instead of varying the intensity of each pixel they varied its area instead, representing it as a still smaller matrix of dots, or employing overstruck alphabetic characters, much like the earlier Bartlane system and "typewriter art." The best know example of this is Knowlton and Harmon's nude, Studies in Perception (1966) (see K&R fig. 3-31). The pixel images also became the basis of a film by Bela Julesz demonstrating cyclopian perception.

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66. Ken Knowlton's first BEFLICKS movie used computer graphics to teach how to use computer graphics to make movies. The language is pixel, not vector, oriented, and uses a 252 x 184 pixel grid.

67. Poem Fields (I967-69) animations involved neighborhood rule based pixel manipulations that created mandalla imagery. Color was added optically.

Stereoscopic animation, where a separate point of view is calculated for each eye, was first produced by A. Michael Noll at Bell Labs (1965). Stereoscopic animation was not new, but when Noll animated the first four dimensional objects and mathematically projecting them from 4D to 3D stereo pairs, he provided a very unique way to actually look into the 4th dimension.

The Bell work spanned a wide range of problems in addition to scientific visualization, typified in the first Zajak film, or language design, typified by Knowlton. Frank Sinden made the educational computer animation movie *Force, Mass and Motion,* which depicted the motion of bodies under various gravitational laws. It prooved conclusively that computer animation was a natural for science education.

Thus by 1965 both vector and pixel computer animation techniques were defined. The simulation of image may be totally abstract and purely 2D, or it may derive from a pictorial representation. With pixels one may simulate all known analog effects (from fades to the traveling glow mattes of Luke Skywalker's light sword), plus some digital image effects that have no analog ancestry.

The first color films

Although color animation could be made by shooting black and white film and optically printing it with colored filters this was a tedious process. The solution was the development of continuous tone color film recorders. were built (independently) by General Electric in Syracuse and the Mathematical Applications Group (MAGI) in Elmsford, New York about 1966. Both of these machines were raster only, and displayed the picture by interlacing each scan line, in other words, each scan-line was drawn successively in red, green and blue through rotating color filters before the next scan line was drawn. Software was progressing rapidly, and in 1968 GE produced a color computer animated film for NASA, *1984*, that depicted the operations of a future space shuttle, perhaps the first movie that featured opaque colored solid objects and polygonal shading (fig. 68). The following year their movies on *Highway Interchanges* and *Hancock Airport* included fog simulation; flight simulation was a definite market area. Other experiments included architecture—

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68. Solid, opaqued polygons, occulted surfacing (hidden surfaces removed), color, lightsourcing (Lambert, single color per polygon) and a moving camera mark the state of the art in l966 systems by GE (left) and MAGI (right).

Donald Greenberg made his first animations using the system. This same GE research unit was later to develop the first successful computer slidemaking system—Genigraphics. MAGI's first films, like *Army Heavy Lift Helicopter Simulation* (1970), reflected the company's research roots; now its president, Phil Mittleman, brought the medium to attention of the networks and advertising community, with some success. It is probably fair to label MAGI as the first computer animation company. The first animator to be employed there was Larry Elan, who was hired about 1974.

GE and MAGI aside, computer animators who wanted color in their movies throughout the 1970s had little choice but to add color optically using gels [probably not do this here but may keep if expand section with typing. fig. space ++ or times square]. The major difficulty of this was not in producing pure color with filters, but with continuous tone, full color. This problem resolved itself at the very end of the 1970s, when Informational International Inc (III), a company that had been building black and white film recorders for over a decade, constructed special full color raster units for a newly formed motion picture group, headed by John Whitney Jr. (the son of John Whitney Sr., above) and Gary Demos. The COM units utilized a small flat faced CRT display that displayed 256 levels of grey, and a color wheel between it and the camera that was also computer controlled (K&R fig. 3-27 shows the arrangement clearly, although the reader should note that the color wheel need only contain three filters, red, green, and blue. The three additional complimentary filters make it possible to shoot interpositive directly. COM units also often have a clear (aka neutral) filter so they can shoot B&W in one pass). Unlike the GE and MAGI machines, the III units were not constrained to a rapidly spinning color wheel; the color wheel was usually programmed to turn on a field by field basis (fig. 69). The III movie group units were also extraordinary in that they could digitize film frames using a flying spot scanner technique (see K&R 3-27 for typical diagram). The frames could then be written back out

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69. One of the most famous images of this period is the III jugler, certainly not their first full color COM recording, but with acton so compelling that the viewer forgets about the technological background. The rendering is Phong, and the juggler is made by rotoscoping witness points on live action. And the tromp d'oeil that ends the scene is a masterpiece of animation.

identically, written out in lower resolution, blockpix style (fig. 70), and used as maps (once they got invented).

The First Animation Languages

Subroutine Packages

During the 1960's specialized languages for computer animation were also developed. Software began to get understood toward the end of the 1950s; the first operating systems, assemblers, and languages were all invented during this period. The first widely distributed graphics software package was a standardized subroutine interface defined by Calcomp (1959)(fig.); a similar package by North American Rockwell Corporation was developed to support the SD-4020 and helped accelerate progress during the latter 1960s. The first animations were programmed in languages like Fortran, the first animation languages were Knowlton' BEFLIX (1964) and Anderson's CALD (196_).

2D and 3D drawing languages

The pioneers also simulated the process of animation. In fact, it was one of their very first tasks. Animation strikes to the heart of computer graphics because it allows the researcher or artist to use the temporal axis to explore variance. But simulation of the animation process goes beyond making variance inside of do-loops and plotting frames of the result. Simulation of animation implies the computerization of ways to organize and manipulate type, graphical objects sets, cameras, animation stands, and cameras, and backgrounds. Tacit here is an understanding of sculpting temporal events; this distinguishes animation from static graphic software;

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70. The blockpix technique evolved from the work of several people, and it is symbolic of the new breed of "digital effects" that emerged around I976. Leon Harman earlier at Bell researched recognizable digital resolutions, but never made animation. Ed Manning performed the effect using an analog optical device in an optical printer. At III, Whitney and Demos did the effect in full color also, only digitally. They first struck pan masters from the OCN, digitied them on the flying spot scanner/COM, averaged the pixels in each square of the output, and wrote out new color optical negatives on the scanner/COM. The effect instantly became a metaphor for the computer's point of view. After frame buffers were invented it could also be done in video.

functional control of temporal parameters are almost as fundamental as color, 2 or 3D objects, or pixels.

The pioneers tackled this problem with specialized languages.

The first **graphics languages**—integrated graphical commands and were not simply subroutine libraries. One of the first of these is Ken Knowlton's *BEFLIX*, written at Bell Labs in 1964. The *BEFLIX* primitives manipulate a 252 by 184 pixel grid, and include pixel read, pixel write, area write, area scale, area copy, area permutation by rule and others. For example the command PAINT A B WRITE 20 means write the value of 20 into a rectangle with its opposite corners at pixels A and B.

BEFLIX is sort of an **animation language** because it may be programmed to calculate temporal sequences. A movie language must contain instructions to specify image change, usually motion, in addition to instructions for image definition. In order to do this a language must have some kind of looping capability, an if-go-to-label, a do-while-loop, a-or-start-repeat (or else it can't iterate). In practice it is almost useless to make a computer graphics language that won't change over time because so often graphics are a vehicle to communicate temporal displacements. **BEFLIX** can be used as a tool for picture representation, enhancement and analysis. But it can also function as a cellular automa test bench; or a tool for movie making.

Other 1960s approaches dealt with manipulating 2D polygons as well as 3D geometry and cameras. A group of animation languages by Sherwood Anderson and Donald Weiner at Syracuse: **CALD** (Computer Aided Line Drawing), **CAPER** (Computer Aided Perspective Drawing), and **CAMP** (Computer Aided Movie Production) employed commands to define basic objects, move them, employ elementary arithmetical operations, iterate and issue frame advances (fig caption: A typical command might read: LOC1 SPHERE 4.2 5.1 6.2 .787. This means to create and place a sphere at location 4.2,5.1,6.2 with a radius of .787 and store it in LOC1. Subsequent handling of this object is then via its name, for example LOC1 TRANSLATE .2 0 0 means to move the sphere .2 of a unit in X.). Movement is accomplished by specifying initial and terminal parameters for variables, and calculating interpolants for each iteration of the do-loop. A slightly more advanced syntax evolved at MAGI called **Synthavision**, it could also define colors, lights, and unions between objects.

The disadvantage of the full graphical language as compared to the graphical subroutine package is that from a programmer's point of view it is one extra level of structure to build for each new functionality; the functionality must not only be defined and perfected, it must be integrated into the language as well. The advantages lie in standardization of how you put things together, and, especially when the language is implemented graphically, in performing graphical operations graphically.

Animation Stand and Optical Printer Control Languages

Another vector of development were languages to control animation stands and optical printers. The syntax of these languages tended to be more defined in the terms of the machinery involved (eg, counters and fields), and not as virtual images. After all, the artwork is in the real world, and the cameras are physical equipment. In LANGUAGENAME, developed by Cinetron, typical commands include table pan and tilt, camera zoom, shutter, and frame advance (aka shuttle)(figure). Computation is employed to calculate eases, simplify skip and repeat framing, and alert the user to problems such as potential temporal aliasing. Temporal control is provided by simple interactive commands. In practice the translation of the graphical layout notation used for optical printers to computer text is more straightforward than that of dopesheet animation because the computerized stand camera operator must still mount the background and cels artwork on the stand, often changing it on a frame by frame basis.

Obviously low level command language also exists for manipulating camera and rigs moving in three dimensional space, however in practice it is semantically equivalent to manipulating virtual 3D cameras and props. Whether it uses mathematical-like notation or studioese depends more upon the pleasure of its users that the physical equipment.

Concept of simulation

Graphics processes may be implemented in hardware or software—in the last analysis this distinction is secondary to identifying the functionality itself, that is, the definition of the variable and its domain. Making animation is a procedural task that can be described with a series of steps. Animation involves manipulating both the data of the image (by drawing or by procedure 2D or 3D environments) as well as temporal variables such as velocities, accelerations, and directions. So thinking about the functional parameters of animation makes a great deal of sense. It is how one directs animation, talks with an animator, and how an animator operates the system.

It is safe to say that there appears to be an efficiency in building new ideas first in the more rapidly malable software, and then implementing a subset of these ideas in hardware in order to achieve efficiency as well as constrain the design. As the hardware becomes more specialized it may become unable to "think about" new ways of solving problems; these in turn are attacked with more general purpose software, and the cycle repeats itself. The first generation of computer animators understood this.

Given software the pioneers recognized they could simulate all kinds of processes. Simulation is a word with many meanings in the moving graphics milieu, but in this meaning it may be thought of as a procedure which models some actions of real life. And so the pioneers discussed the simulation of drafting, of images, of the lens and the camera, of lighting, of painting, of page makeup, of the cel animation processes, of the physical world, of abstract and artistic processes, of thought.

The simulation of drafting

The low level graphic subroutine packages simulated the drafting table. The very lowest level commands only draw lines, but slightly higher level subroutines defined arcs, circles, conic sections, and constructions like perpendiculars, tangents, and angle bisection. Still smarter software can simulate the typesetting machine, calling letters from font memory and, given parameters like letter width and justification method, can calculate how to place them correctly. Lines can be drawn which are equations, X and Y axes, even entire line graphs, scattergrams, or bar charts. In fact coupled with the computer's ability to make decisions, virtually all facets of drafting may be computerized, including blueprints, maps, and perspective drawing. Drafting simulation is not really animation, except when it moves.

The simulation of lens and camera photography

In addition to representing line drawing and images, the pioneers quickly grasped they could simulate the camera and lens, and in turn make pictures of 3D environments. The first simulation of lens perspective on a computer was accomplished by Larry Roberts and Steve Coon at MIT (1963), and by Bill Fetter at Boeing. Lens simulation allows one to describe an object with three spatial coordinates and to calculate its projection on an imaging plane.

Like a real camera or eye, the synthetic camera may be moved in space and pointed in different directions; this gives it 6 degreees of freedom (3 position, 3 orientation). This is codified by Anderson in CAPER (196?). In addition to the lens the virtual camera may also have a shutter, aperature, and directionality it moves the recording media. From the animator's point of view the manipulation of these parameters is semantically equivalent irrespective of whether the camera is real or virtual.

Very little other work on the mechanics of the lens and the camera occurred during the 1960's. Coons published extensive notes on implementing different kinds of perspective xforms, but the work has found more application in CAD than in animation and graphics. Anamorphic lenses, such as those used in cinemascope, compress the X but not the Y axis, and are modeled by scaling the data in X after the perspective transformation. A number of spherical projections are well known and used in computerized cartography, but simulations of things such as a fisheye lens are absent from the computer graphics literature; one of the few exceptions is the Omnimax projection that calculates a planer projections designed to be projected onto the inside of an OmniMax hemisphere (1984). Another rather obvious and undone improvement would be to incorporate the mechanics of a view camera into a computer animation system—it would provide a major benefit in composition.

Simulation of depth of field was achieved by ___ in 19??, and motion blur—the simulation of an exposure integrated during a shutter time when objects or the camera are in motion was solved in _____, mostly by the Smith and Catmull lead Lucasfilm group. Little if any work has been done yet in the simulation of focal plane shutters, or the exploration of perspective procedures used in Pompey [sp & what perspective there?] or by M.C. Escher.

Some computer animation systems provide a facility whereby it is possible to script more than one camera in an environment. One advantage of this is that it is possible to watch how the principle camera moves as well as watch what is visible thru its lens. The term gnomon (??) is sometimes used to refer to an object visible in an environment which is a camera (fig).

The Seventies

Hardware trends

By the late 1960s Sutherland had moved to the University of Utah where he helped establish one of the first programs devoted to computer graphics. Another venture, this one with David Evans, was to found a company to build interactive vector graphic display systems. Evans and Sutherland Inc shipped their first units in 19xx.

IBM introduced an interactive CRT for the System 360 called the 2250 in 1965? (fig. 63), Digital Equipment's VB10C hooked onto their PDP10 in 19??, and startups like Vector General also played the field.

But E&S was the company to beat. By the late 60's they perfected an interactive real time system able to display colored solid objects and focused on realistic flight simulation. In 197? they introduced a second generation vector machine, the Picture System II, which hooked to a DEC PDP11, and was faster, cheaper, and more flexible. The highly interactive picture system II made an excellent animation preview machine; being monochromatic it was not the perfect film recorder but doubled as such anyway for companies such as Robert Able Associates, who filmed the images single frame style through colored filters.

But from a standpoint of animation the most radical breakthrough in interactive displays came in 1982 when Silicon Graphics' IRIS fused a display list machine with a framebuffer (the evolution of which is discussed shortly), a strategy which combined the best of both into a single platform built around the new 68000 processor. The IRIS broke all previous price barriers and incorporated interactive real time display, color, and video output into a single machine that by the late 1980's was the dominant platform for making computer animation (fig. 64).

The first color camera you could buy was built by Dicomed Corporation (now part of Crossfield-Dupont). Their first color camera was built at the insistence of Steve Levine, then at Lawrence Livermore Labs, and could display colored vectors as well as color raster pictures at a 4000 pixel square resolution. Serial Number 2 ended up at NYIT, and serial number 3 became the Digital Effects Inc. machine.

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63. Permutations resulted from a collaboration between John Whitney and Jack Citron of IBM. The images were filmed from the face of the 2250 CRT and optically printed to add color. Whitney is one of the few people whose work bridges analog and digital media. One of his major themes is periodic form (see also fig. ??). To the extent one might label his earlier work "analog computer graphics," one might also label this as "simulated motion graphics."

64. Combining a display list with a frame buffer makes color easy and previewing hidden surface geometry practical.
The idea is trivial to understand but it took a startup company--Silicon Graphics--to realize it.

The perfection of this technology coincides with the first generation of computer animation companies—MAGI, Robert Able Associates (with Bill Kovacks), III, and Digital Effects (founded by Judson Rosebush, Donald Leich, and Jeffrey Kleiser), who all end up working together on *TRON*, the first feature film with a major computer animation component.

In 198?, a new generation of raster non-programmable film recorders from companies such as Dunn, Matrix and Management Graphics plummeted prices and simplified operations. The new generation of raster recorders, coupled with the personal computer, exploded the color slide presentation and business graphics marketplace. And hooking a 35mm pin registered Acme or Mitchell camera onto one of these units only required the skill of a good machines, a tactic taken by newer generation companies, like Intelligent Light. Computer animation remained difficult, but the financial and technical hurdles that needed to be overcome were vastly diminished.

Image Digitizing

The digitization of 2D images is actually quite old; early examples probably predate the Bartlane transatlantic cable (1921). These early systems represent the image as a matrix of numbers representing the intensity values at each pixel, and a TTY style output device reproduces the image using either special characters or alphanumeric overstrikes.

Adding a computer provides a better way to not only store and transmit pictures, but also to analyze them. A rotary drum scanners which could digitize individual images was built by Roland Kirsch at the National Bureau of Standards (1957), and in 1964 the Jet Propulsion Lab in California used pixel matrices to represent television pictures from the Ranger Moon probe. Using frequency domain techniques the pictures were computationally enhanced to make them look better and reduce interplanetary noise. Again Bell Labs demonstrated a wide range of applications, including using half toning techniques to make dot patterns on the SC-4020 film recorder (1966). Digitizing film and tape proved to be a more formidable task, although single digitized images began to be employed in computer animations as image maps after 19xx.

The first practical machine to capture a sequence of film images in registration was the above mentioned III film recorder, built for the motion picture group (1976?), and which worked as a flying spot scanner with a digitizer coupled to the output of the photometer behind the film plane (figure ??). The III machines saw only occasional use in the image capture mode (fig. 70 of *Westworld* is one of them). After III liquidated the motion picture group in 198? the COM units were acquired by Digital Productions and Omnibus. In one application Omnibus used them to capture live action footage which was image mapped (using Digital Effect's Visions software) onto a metallic spacecraft for *Flight of the Navigator*. Following the bankruptcy of Omnibus they were sold to ____, where they are still running at presstime. Aside from these machines, which were never really marketed, the only other practical device for digitizing sequential frames of motion picture film seems to be the scanners built by the computer graphics group of Intelligent Light and Magic, a division of Lucisfilm. These machines reached their full maturity beginning in 198? on the films *Willow*, *Indiana Jones and ...*, and *Abyss*, in which ILM perfected digital blue screen process at film resolutions. The effect and implications of this are not yet fully felt, but it is obvious that the complete digitization of the optical effects process overcomes a host of traditional problems and will vastly expand the range of the effects vocabulary. [Add Terminator].

At the end of the 1980's a host of vendors, including Nikon, Kodak, and others introduced low cost, high resolution slide digitizing devices designed for use with personal computers, and although your author is unaware of any specific utilization of these for motion picture capture he suspects that the integration of a pin registered motion picture shuttle into these devices could provide a very cost effective solution. The real reason this hasn't happened is more likely due to the fact that video has replaced film as a preferred medium of production for everything but theatrical release, and for video the image capture problem is easier to solve. [Develop Photo C/D and other Kodak strategies.]

The Simulation of Cel Animation

Although much of the pioneers' efforts were directed at the new possibility of 3D animation another faction tried to simulate the cel process. The problem, to the extent its purpose is to assist from the drawing stage forward, really requires a full range of graphic art creation and compositing tools to be operational. In order to solve it one must also fully understand classical cel production before movement of cels and computerization of inbetweens could be accomplished. In retrospect we see that the perfection of the parts was accomplished independently of any "grand plan". Perhaps this is because each of the parts represented challenges themselves.

Computerization also eliminates several major technical limitations of the cel process. In the real world the number of cel layers is limited because the acetate is not actually perfectly transparent—in fact the problem is severe enough that the paint used on the fronter cels has grey added to it so it matches colors of the cel behind it as seen thru the layer of acetate. The thickness of the paint also causes cels to lie unevenly, sometimes creating internal light flairs. And dust, dirt, and handling damage are constant problems. Obviously no such problems exist when the cels are virtual. Finally, computerization is readily applied to the information management aspects of the problem, including scripting, layout of action (doping), and routing materials.

This problem was tackled by the Canadians: Ronald Backer at MIT building GENESYS (1970), and Marcelli Wein and Nester Burtnyk at the National Research Council in Ottawa with a system called MSGEN (1971). Backer system ran interactivelly on the TX-?, and on the GENESYS Demo he shows how to trace a motion pathway using a data tablet, how to draw polygon shapes, how to interactively connect shape-cels to a timeline, and how to play action. The system should not be confused with solving the problem in a practical sense–it has no filled areas, no color, and only one object at a time, but it is significant in that it incorporates both the concept of interactive graphical lexicon and temporal commands into a single system. It is not the first graphical lexicon but it is the first language (interactive or batch) to incorporate the design of temporal shapes in addition to graphical shapes—that is why it is sometimes sited as the first computer animation language. Temporal shapes include action pathways and eases; graphical shapes comprise the geometry of the objects. In GENESYS, the temporal shapes (aka actions) and graphical shapes (objects) are freehand sketched and edited (or destroyed) interactivelly; previewed together they form animation. The speed of the preview may be controlled interactivelly, and animation may be rocked forward or backwards in real time.

Wein and Burtnky's MSGEN adopted the premise that animation may be structured as a series key positions which represent the extremes of action. In the classical animation studio that chief animator drew only these key drawings—for example, the beginning and end of a salute of a character—and the intermediary drawings, or inbetweens, were prepared by an assistant. MSGEN defined the two key objects digitally and computationally interpolated from one extreme to the other in successive frames (figure); in practice MSGEN could handle multiple objects simultaneously. Another development was the development of an underlying, invisible skeleton, to which the polygons were attached. When the skeleton was animated the attached polygons moved with it. The system worked with lines as well as filled polygons. MSGEN did not have a compositing capability—it outputted to black and white film and compositing and colorization was done optically. The system proof was directed by Frenchman Peter Foldes in l973; the film *Hunger* (1973) successfully exploited the strengths of the new technology, particularly methamorphsis, while avoiding the cutseyism of the Hollywood cel style (fig. 85), and became the first computer generated film nominated for an Academy Award.

As the 1970's progressed it became obvious that a full-fledged cel system would require more components. At Xerox PARC in Palo Alto Alvy Ray Smith and Dick Shoup invented **paint** systems, Dick subsequently founding Aurora and Alvy, along with Ed Catmul, a Utah grad, built a resource at The New York Institute of Technology (NYIT), where the cel simulation problem was attached with vigor: The NYIT cel simulation effort was inspired by the school's president and founder, Alex Shure, and was one of a trid of developments in the institution's Computer Graphics Lab (the others being 3D and paint). The NYIT TWEEN software was initially written by Ed Catmul (1979) and others, including Garland Stern, whose SOFTCEL introduced soft edged antialiased color compositing. The laboratory pioneered a production pathway from computer to frame buffer to frame video recording (date), using IVC 9000 two inch helical scan VTR's. (figure, eg, from the Works). TWEEN was exported to several other sites, one of the most important being the Japan Computer Graphics Lab (JCGL) in Tokyo, and the nucleus of people who are familiar with it constitute a major pool of experience in cel simulation.

Computer Creations Inc. (CCI) in South Bend was another facility that pioneered cel simulation, and like NYIT computed directly onto videotape (year). The CCI facility was headed by Tom Klimak and focused almost entirely on commercial production. CCI recorded onto an Ampex ESS-2 digital videodisk and then edited to videotape when the disk got full. CCI's technology is very clearly illustrated in the short *Dilemma* (1981), directed by John Halas (fig.

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85. Hunger. Computerized key framing between extremes. Data is stored in point/polygon form, and eases are calculated using linear interpolation.

86). It is worth noting that Jim Lidner and Suzanne Gavril, later to found Fantastic Animation Machine in New York, began in the business as CCI's New York marketing team.

Similar systems evolved in England, with Alan Kitchin's ANTICS, eventually propogated to North America and Asia;

All of these systems—MSGEN, NYIT, Antics, Computer Creations—share a common strategy of drawing polygon data artwork and employing the computer to inbetween 2D polygons, and then scan convert, color, composit, and record them. Most also include some kind of skeleton concept, and have a smoothness of feel and solidness of color that associates them with computer animation.

Obviously both the interpolant and the skeleton concept can also be applied to 3D animation, as with Stern's BBOP language.

A quite different strategy occurred when Hanna Barbara Productions, the largest cartoon producer in Hollywood, commenced a project to automate aspects of their cel process. The Hanna Barbara approach was lead by Donald Greenberg and others from Cornell including Mark Levoy and Chris Odgers. Their strategy was also to focus onto video but to sidestep the inbetween issue entirely and automate a narrower focus. The artwork—cels and backgrounds—were produced using classical methods, except that the cels are unpainted. The black and white outline drawings or cels were scanned in via a TV camera, and backgrounds are scanned in using an RGB digitizer. All of this data is stored on digital disc. Sections of background can be assembled into oversize pannable art. Since many cels are used over and over the number of cels digitized for a certain cartoon is far less than the number of frames.

The computer is next used to ink and paint. The painting involves an antialiased edge and uses an algorithm with frame to frame coherance, so that an operator only has to color the first cel in a series and the computer extrapolates the color in subsequent cels.

In addition to the cels and backgrounds a digital dope sheet is created; like classical dope sheet this coorelates cels, backgrounds, and frames and directs the compositing operation. Indeed, for a limited animation style like the Flintstones, once a basic library of standardized bodies, heads, lips, and eyes has been digitized into the system, doping became the main chore. A simple compositing algorithm simply loads the background and cels back to front,

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86. Dilemma illustrates the use of 2D shape interpolated key frame animation in the video domain.

successively compositing atop into a frame buffer, and records the frame on a digital video disc or tape.

The advantages of the Hanna Barbara process as oppossed to the previous computer methods was that it ignored the difficult inbetween problem, leaving it in the domain of the human. struck at the gut of the problem, eliminating the non-creative manual art and camera operations, and conquering the previous limitations to the number of cel levels, flashing, constrast ; and cel wear and tear on cels. It also afforded an ability to preview, edit, and experiment more easily. But inbetweening was left entirely with the humans.

In terms of personal computers, the first animation system for the home market was the program Movie Maker, written by Guy Nouri and Eric Podietz of Interactive Picture Systems for the Atari 800 (date). The product was based entirely of creating and manipulating sprites. In terms of the IBM/PC no significant product has ever emerged, perhaps because the graphics engineering effectively prevents it. In terms of the MacIntosh, cel animation may be accomplished by software sprites or by rapid replacement of the whole image. One approach builds around the more general purpose HyperCard, which can achieve animation by changing cursors, button icons, font/sprits, or entire cards. HyperAnimator is an extention of HyperCard specialized to do lip sync speech of talking sprites. Macromind's Director (formerly Video Works) is a standlone system that incorporates a virtual dope sheet to animate multiple sprites on the screen (fig 87). None of these systems support polygon graphics or inbetweening, although it is possible to import a sequence of pictures that have been previously prepared externally and play them in sequence.

As we go to press the jury remains out the question of automating the inbetween process. One school of thought argues that the inbetweens contain so much original information they cannot be derived simply from the extremes. The problem is especially complicated by many of the vagrancies of drawing in 2D—what happens to facial features for example when a head "turns." Another school of though believes that the "original" information may not actually be so original, it's just higher level information and that as soon as we can program computers to use more expressive actions ("look puzzled, then turn your head to the camera"), instead of geometric actions (interpolate line from point

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87. Macromind's Director is an example of a turnkey animation system. A virtual dopesheet controls where cels (2D pixel arrays) get composited overtop backgrounds.

A to point B) then the problem will solve itself. Perhaps by then the computer will also be writing stories, designing characters, and making its own animated movies.

Input of space time coordinates

[to Backer]

Obviously, computer animation employs common 2D input peripherals including the light pen (1953), the tablet (1964), and the mouse (1968), as well as some 3D point input devices such as the space wand(19??). It is significant to note that many of these can be sampled rapidly in time and that such a series of discrete samples may be used to control either interactive processes in real time or provide sequences of values which are applied to an animation parameter which is subsequently batched. Familiar examples include moving a stylus in a paint program, and the use of a space wand to sketch actions in 3D space which are followed by an object or camera (fig. 71). Another example is the gimbeled body harness (K&R fig. 3-28), which includes multiple shaft encoders which are sampled in tandem, and the data glove (fig. 72) and body suit. An alternative to sampling peripherals is to employ witness tracking (fig. 80). In all of these cases the basic idea is to sample in real time and then use those samples to control virtual actions. A system may be configured to do this interactively and in real time, or the values may be saved, edited, smoothed, or otherwise worked before doping and computation of final output.

The simulation of lighting

The success in making perspective three dimensional vector graphics in the early 1960s created a demand for still more

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71. 3D want may be used to make gestures in space. These gestures may then become pathways for computer animation to follow.
72. Data glove, like a body suit, fits to the hand and senses the orientation and positions of the joints of the hand, making it an extremely versital input peripheral.
80. Witness tracking is done by strategically placing easily recognizable points on a subject and scanning the subject, usually with multiple cameras while the subject is in motion. The computer locates the witness points in the picture and keeps track of them from frame to frame. The system shown in the illustration can actually track a golf swing and display it vector graphic style in real time. (Courtesy of Biomechanics Inc.).

realistic graphics, and during the next two decades much of this quest focused on the representational aspects of synthetic reality.

A central task was a computing procedure to remove lines in perspective pictures that would be not be visible if 3D objects were opaque. This so called "hidden line removal" procedure was solved by Larry Roberts at MIT in 1963 (fig.), although it was too slow to run interactively. The extension of this problem to objects which were themselves opaque and not made of lines was most successfully tackled by three groups: General Electric, MAGI, and the State University of Utah at Salt Lake City.

GE's approach was to construct a interactive flight simulation system capable of displaying up to 40 full color solid objects in real time with their hidden surfaces removed and with the visible surfaces shaded to approximate reflected illumination from an imaginary light source (see fig. 63). Mythologically the purpose of the simulator, completed in 1967, was to train astronauts to practice landing on the moon, a useful tool because you could not practice the real thing, and it was a prototype for a new generation of training divides which integrated computer driven synthetic visual environments into a servo controlled shaker platform complete with a cockpit and working dials. The GE unit also produced high resolution film animation using a custom built high resolution raster CRT, as described in detail above. [or move to here better]

MAGI evolved a hidden surface capability that involved ray tracing, a technique originally used in research of nuclear radiation. Objects were built out of predefined primitives like spheres and planes, although the light shaded results were facet shaded. A command language software, called *Synthavision*, scripted objects and actions and was batch executed on an IBM 360; output was via a custom built CRT, also described in detail above. [or move to here better]

After graduation from MIT and short stint at Harvard, Ivan Sutherland moved to the University of Utah, where he and David Evans created a computer graphics department (date), as well as the Evans and Sutherland Computer Corporation (date), which undertook to manufacture graphical display systems (date), frame buffers (1973), and full fledged flight simulators (date). At Utah the hidden surface was reexamined and two new approached explores. One, devised by John Warnock (later to become the founder of Adobe and the father of Postscript) employed an area search (1969), another, by Watkins, utilized scan line sorting (1970). Like GE and MAGI the

Utah facility was able to generate film animation, again using filters and a custom CRT.

In the early 1970s the capabilities of color frame stores and color film recorders made it easier to view 3D solids. The ensuing search for realism focused on the representation of surface and lighting: chiaroscuro (shading), shadows, transparency, textures, and light reflection emerged as major variables.

Chiaroscuro, the treatment of light reflected from a surface, was the first embellishment to be explored in depth. Utah, GE, and MAGI all implemented polygonal shading (aka flat shading, Lambert shading) in which an entire (polygon) surface is uniformly shaded according to its angle with the light source and the eye, but it was at Utah where lighting and rendering got defined in a series of PhD thesis. First, ?? Gouraud introduced an interpolation method which varied the brightness within the single polygons (1969). Gouraud's continuous shading scheme eliminated the discrete brightness jumps between adjacent polygons and increased realism. Then B. Phong extended this concept to incorporate specular as well as diffuse surface reflections (1973). Transparent surfaces got implemented in 1972 by Martin Newall (who also made the famous teapot). Shadow simulation was resolved by Bouknight and Kelly at IBM (?) in 1970. By the mid 1970's Utah no longer had the corner on the market, and in addition to Cornell other centers included Chuck Csuri at Ohio State (whose first graduate was Tom Defanti). Utah continued to produce excellence however: in 1977, Jim Blinn defined image and texture mapping, two related techniques which incorporate pixel graphics into the 3D arena. Image mapping parametrically wraps 2D pixel images onto a 3D surface (see also fig Mirage); texture mapping employs 2D matrices of normals, which are used to pertubate the normals in the Phong calculation. Again we refer the reader to K&R for detailed diagrams and explanations; technologically Blinn`s orange made him famous, because it showed there was a way to simulate complicated surfaces without resorting to huge numbers of polygons. The rediscovery and extension of ray tracing by Turner Whitted of Bell Labs (1981) provided a way to model light in a more computationally exhaustive manner, and simplified the implementation of reflection and refraction—instituting a decade of polished chrome spheres reflecting other polished chrome spheres, possibly with a prism or lens thrown into the scene for good measure.

By the end of the 1970s it was clear that many of the parameters of the visualization of the real world had now been discovered, although new hardware architectures, in particular the frame buffer, and new modeling techniques, in particular fractals and parametric surfaces, were forcing a reappraisal of computational techniques, many of which involve gross approximations of reality as well as "dirty tricks"—things which compute a picture that looks good but which are flagrantly inconsistent with the real world. After all, nature doesn't make marble by image mapping it.

One of the new goals was the elimination of aliasing—in the spatial domain the jaggies and in the temporal domain the judder. Anti-aliasing hidden surface algorithms combined with a Z buffer (?) were introduced in 1977 and 1978 in papers from Frank Crow and Ed Catmull. Newer lighting models, like the Torrance Sparrow, addressed the material composition of the objects, and increased complexity helped to make scenes more real. Need some better copy. By the 1980's it is correct to say, that with regard to simulating reality, that some pictures could fool some people some of the time.

Radiosity, atmosphere.

Second generation animation languages

Second generation animation languages emerge in the l970s. Central issues involve the replacement of graphical lexicons for textural ones, and the introduction of temporal commands. Temporal commands can be worked in either interactive or batch modes, and as the decade progressed understandings about how to managed time increased. MOP (MOtion Picture language), written by Ed Catmul at Utah (1972) formalized temporal parameters and allowed single temporal commands can be aranged in any order with regard to their start and end times (just like objects can be stored in any spacial order). A temporal command includes a variable name for itself, the action type (eg translation, rotation, size), the start and end values (eg beginning and end rotation values), an easing rule, and a duration in frames. In addition to graphical commands (to make objects), and temporal commands (to make actions), the language (or system) requires a [classname?] command to connect an object, an action and a set of frames. Catmul's commands to do this include commands to superimpose independent motions onto a single object, commands to apply a single motion to multiple objets, and [research this out].

During the l970s in the commercial animation sector both Digital Effects, using Visions, and III, using ASIS, adopted textual semantics to describe actions. Both strategies involved extentions to highly procedural languages, APL in the first case and Lisp in the latter. Experimental systems of Visions were built using 5x5 transformation matrices and five column data, so that temporal definition could be added to the entire system. The downside of that approach is that it puts a lot of computation outside the critical problem area—and that is how to define and store temporal variance. Eventually Visions defined procedures much along the Catmul line to calculate arrays of parameter values, and to then employ those values by name in expressions that defined animation.

More sophsicated solutions emerged from ASIS, authored by Craig Reynolds and now the guts of Symbolics' system. ASIS allows an animator to organize actions in continuous (as opposed to discrete) time, and for actions to be nested inside other actions and relative to them. Scaling and translating of actions is encouraged, furthermore, actions can cue other actions.

The Video Revolution

The frame buffer and recording on video

Today's reader who wonders why all of the previous sections of this chapter review the methods of outputting to film are reminded this simple fact: until the mid 70's there was no way to interface a computer to video, and it was not until the 1980's that the synapse between the computer and video became practical. Unlike the interface to the stepper and the CRT, this ultimate link between digital computer graphics and video involved fundamental new technology.

The basic element of this interface is a **frame buffer**, a quantity of random access memory with two basic properties: it is organized so that a computer can read or write to it as if it were a pixel array, and secondly, this samesaid memory is continuously read or written through a second port and converted into a video signal that is routed to a video monitor (see fig. 3-99 thru 3-107, also K&R 2-6). Since 1973, where they first came into being, frame buffers have shrunk in size from about a yard of rack space to one card that plugs into the computer's backplane. Synonyms include the terms frame store, video still store, and video memory; a virtual frame store is one without any video output, essentially an entirely software pixel matrix.

Unlike a refresh display, a frame buffer does not execute a variable length sequence of instructions, but rather continuously coverts the contents of a fixed size memory into a predefined TV raster. The frame store can be updated in batch or interactive modes, however, the changes a computer makes to the video memory are immediately visible on the raster color monitor. If the number of screen changes are modest they may all be performed in real time, like with a paint system. If the changes require more than 33 milliseconds to compute, the output from the frame buffer must be single frame recorded because the time is longer than the 30th of a second frame rate.

The first frame store was a three bit deep unit at Bell Labs built around 1970. Another early machine was constructed at the Architecture Machine at MIT, but the most influential unit was a 640 by 480 by 8 bit deep frame store built by Alan Kaye and Dick Shoup at Xerox's Palo Alto PARC in 1973 (fig. 82.5). The Xerox machine used shift register memory and had lookup tables for indexing colors. That same year Evans and Sutherland began building frame buffers and delivered a prototype to the University of Utah in 1974. It was also an eight bit machine with lookup tables, but with random access MOS memory instead of shift registers, and with RGB outputs which could be encoded into a color video signal. The next six E&S machines where sold to the New York Institute of Technology (NYIT) computer graphics lab, lead by Alvy Ray Smith and Ed Catmul. The frame buffers were incorporated into a video animation facility that included painting, character animation, and three dimensional capabilities. By using three of these frame buffers together (with identity lookup tables) NYIT was able to make a full color computer animation system that output onto video (197?) (fig. 71). In order to record the video NYIT employed the new IVC-9000 video tape recorder, a helical scan machine that recorded single frames on 2" videotape.

Historically, the cost of frame stores has been highly correlated to the price of memory, and as chip densities increased and memory prices declined, graphics image memory became increasingly attractive. The frame buffer strategy was quickly adopted by the teenage hacker/hobbiests. In 1977? the Apple II personal computer included a built in ?? by ?? by 3? bit bitmap display and in more recent years almost all personal or desktop computers have been engineered with bitmap displays, from

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82.5 The Xerox PARC frame buffer allowed users to paint interactivelly on the screen.

71. Video computer animation requires a computer with software, a frame buffer, and a single frame video tape or disc recorder. Ironically, single frame video recording is more difficult to do than real time video recording, so making video animation is actually more complex than simply recording the output of a real time device like a paint program.

monochromatic rather course resolution to full color 1280 x 1024 displays. The only problem with almost all of them is that the video signals they output are totally incompatible with the video signals used by broadcast television.

Video image digitizing

In the video domain, the complete raster input/output cycle becomes practical with the advent of the frame buffer which is able to grab a video frame as well as output one. The first frame buffer able to digitize a single frame of video is ???. The ability to digitize a sequence of frames requires either a) multiple frame buffers, b) a way to unload the frame buffer on the computer side as fast as the video digitizer is filling it back up, or c) a single frame playback capability on the video tape recorder. It is also essential that the video frames be in registration, a function of accurate time base correctors. This technology begins to come together in the research lab about 19??, where the first digital video sequences are recorded, and they become an everyday piece of trade as digital video systems reach the hands of broadcasters and post production facilities in the mid 1980's.

Digital Video Effects

The first digital frame buffers in the video industry were buried inside time base correctors. The first systems to exploit the picture manipulation possibilities of the frame buffer appeared in 1978, first the Vital Industries SqueezeZoom, followed the next year by the Quantel DPE-5000 and the Grass Valley Mark I. These **digital video effects** (DVE) systems represented a breakthrough for the video industry—suddenly several basic graphic operations available in all other graphic and cinematic media became possible in video, particularly the facility to size and reposition the real time video image, and the ability to freeze frames or leave trails. Freeze frames are done by simply turning off the input digitizing side of the unit, leaving a single frame captured; trails are done by overwriting into the frame buffer only the area of the video signal itself (see K&R figure 6.0). Some of the machines could also be cludged to do blockpix.

The leader in the field appeared in 1981, when Ampex introduced the **ADO**, a DVE unit with the added ability to perform 3D rotations as well, that is, tumble moving video images in perspective, as well as size and reposition them. Actually, the ADO's rotations are pseudo 3D calculations and not equivalent to those described by rotation matrices, but they can be convincing.

In practice a DVE is controlled in real time using a joystick, although it can also be addressed numerically by a computer. Temporal control is facilitated by the positioning of key positions, and eases between them may be triggered by a computerized editor—that is the image frame can move from a start position to an end position automatically once cued. The mundane work of the ADO is the video insert over the shoulder of the television newscaster. The insert image is digitized on a frame by frame basis in real time, scaled and translated in a frame buffer, and DTAed back into video (fig. 32). In a post production environment, the ADO is an everyday workhouse of computer animation, manipulating artwork that is often composited with output from a 3D synthesis box.

In general special effects video hardware tends to be rather single minded in just what a piece of equipment can do; the good news is that it does it in real time. Typical of this trend was an even more specialized video image mapping device introduced by Quantel in 1983. Called the Mirage, it works by mapping the video image onto a grid of polygons. The grid corresponds to the video image, yet it is flexible and may be manipulated in three dimensions, creating effects such as wrapping the image onto a sphere, unwrapping an orange, or turning a page (fig. 33). The action of how the grid moves is defined by a procedure written in Pascal, and which is compiled to produce an machine instruction file unique to the Mirage. Typically a move is defined by two extremes, an initial and terminal position. Many different animated transition effects can thus be created and stored; when they are loaded into the Mirage

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32. Real time translation, scaling, and "rotation" of video is accomplished by devices like the Ampex ADO. This image, from a journey through a realistic art gallery interior by John Sanborn and Dean Winkler puts the ADO thru more than normal paces. Each piece of art of the wall is a single video channel that is properly alligned in perspective before being pasted into the set.
33. The Mirage is a real time device which maps a video image onto a predefined polygon mesh. You can't see the mesh only (reading left to right) the video that is stuck to it as, so that as the mesh aninimates so does the video. This growing up and untwisting action reminiscent of a flower growing. In reverse (from [4:2] onward) the video image behaves like the last water running out of a drain. This particular transition is number 34 on Broadway Video's catalog of Mirage effects--meaning that this particular transition already exists and can be applied to *your* program. Courtesy of Dan Vaughn and Peter Rudoy at Broadway Video.

each appears on the console as a selection button. The editor selects the video signal that is to be mapped onto the grid, selects which Mirage transition is to be employed, and controls the action between the extremes using a slider bar, either interactively and in real time, or by keying in durations and cue times and letting the editing computer do the dirty work. The Mirage is a speciality machine and this strategy of controlling the image by controlling only a template is intreging.

Note that all of this video equipment uses a digital component representation in the frame store, and not RGB.

Turnkey animation systems

The introduction of 3D computer animation systems into the video industry occured during the early 1980's. In 1983 Bosch introduced the first 3D animation workstation directed at the video market, an anti-aliased interactive real time 3D solid modeling station called the FSG4000. The FGS4000 included menus to assist in model construction, lighting, and action, and it could animate objects, lights, colors, transparency, and camera positions (fig. 35). Objects could be controlled heirarchically and video images could be mapped onto polygons. When the images were too complex for real time preview, simpler objects may be used to preview the animation in low resolution in real time, and the more complex objects substituted for final production to videotape. Many video experts learned about batch programming for the first time in their lives.

In 1984 Cubicomp introduced a "low end" 3D computer animation system configured around an IBM PC-AT and incorporating single frame video recording. The system lacks the speed and data volumes of high end systems, but it could still animate very presentable images using smooth shading and image maps. Suddenly computer animation became assessable to the masses.

But the greatest expansion of 3D capability in the video production environment occurred after 1985, when animation software from Wavefront and Alias, running on the Silicon Graphics Iris exploded in the video market. This strategy of a turnkey system built around a fully programmable computer with languages,

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35. The Bosch FGS4000 brought real time computer graphics to the video industry. The system excels at producing high volumes of relatively simple computer animation and is a favorite with industrial and medical producers, as well as broadcasters. (Courtesy Judson Rosebush.)

memory, a special real time display list, and a video out frame buffer seems to combine the best of the more interactive needs of video as well as the more programmic approach of the classical computer animator. In actuality video computer animation systems trailed the film approach by almost three decades but by the end of the 1980's there was little need for the animator to work with film at all unless it was desired to do so.

Motion Control Languages and Interactive Systems

Despite Sketchpad and Genesys, interactive graphics were to play only a flirting romance with animation during the sixties and seventies. The exceptions to this included the IBM 2250 display driven by a 360, used by Janice Lourie for textile research and by John Whitney for his first animated film *Permutation* (I967), programmed by Jack Citron, the first of several associates, another later one being Larry Cuba. Another approach was heraled by Tom Defanei and his Grass (and later RT1) language and stressed the performance aspects of graphics coupled with video.

More sophsicated animation languages emerged in the early I980s, including Bill Kovack's WHATEVER, developed at Robert Able and Associates an d running on the Evans and Sutherland Picture System II. The crux of this approach was to manipulate complicated multi-axis cameras and multi-axis props, both virtually and in the real world, and to preview and test shots. In these languages the camera can move independently of the artwork or model. Terms used to identify motion may be drawn from the film industry (pan, dolly, zoom), or they may be computerese (translation, rotation, scale). Arguments should be expressable in real world or virtual space.

Although batch systems dominated commercial animation in the I970s, interactive systems emerged all-powerful during the I980s. The most significant factor contributing to this trend was the introduction of a moderately priced interactive display list machine from Silicon Graphics, the Iris (1982?). The Iris was an integrated workstation that combined an off-the-shelf 68000 series computer running the UNIX operating system, Ethernet, a raster frame buffer and CRT, and special purpose chips for display list processing. A wide variety of software could run on this machine, among it special third-party software products specializing in computer animation.

The first of these was from Wavefront, a company founded by Bill Kovacs, the principle architect of the Able System (198?). The Wavefront software retains motion control overtones and conceptualizes action in terms of channels—each channel corresponds to a degree of freedom, eg an XRO joing rotation. But it provided something the batch systems did not: it allows an animator to preview interactivelly.

Another product of this genre emerged from Toronto based Alias Corporation, and featured more extensive use of interactive windows and menues, with interactive controls for object placement, lighting definition, and ease construction. The Alias System includes a virtual dope sheet, which allows the animator to employ a spread sheet style matrix to specify values for parameters, much the same way the classical animator uses it to specify cel contents. Values for extreme positions can be entered, easing rules defined, and individual frame values are calculated and stored in the dopesheet (figure: The Alias dopesheet contains one row for each frame and one column for each parameter (or channel). It is similar to classical dope sheet except that classical dopesheet has one column for each cel layer. One advantage of the virtual dope sheet is that changes made to parameters, for example the values of an ease, can propogate forward into the dope sheet immediatly.).

Other vendors active in marketing Silicon Graphics based animation systems include Neo Visuals, now a subsidary of 3M Corp, Vertigo, owned by Cubicomp, Soft Image, a Montreal startup, and TDI, a European forey. Like the Wavefront and Alias, these systems also employ a wide variety of interactive editors, including sophsicated ease construction. System differences include subtle but significant strategies in modeling, with different vendors favoring polygons, splines, or lofting approaches; rendering and lighting tools also vary. Time is treated much the same by all four of these vendors, derivative of Genesys, and quite different from Symbolics, which we have already discussed above. Systems such as Symbolics and Intelligent Light, a Fairlawn, New Jersey company based on an Apollo computer.

Preview aside, very little of the animation made on any of these systems actually computes in real time.

PC Animation Systems

With the advent of the IBM PC in I9XX, the MacIntosh, and the Commodore Amega, computer animation became available to the hobbiest, student, artist, and independent. Besides programming in language like C or Fortran, animation languages for these machines include Cubicomp (for the IBM PC), ____________ for the whatever, etc. Semantically these packages have no significant advances in the treatment of time, relying primarely on dolooping to achieve successive frames, and whatever there is to say here about eases and other temporal commands. So run this down. Representationally these packages are able to produce 3D shaded images, but are quite limited as to what can be accomplished in an interactive mode.

Inovations in animation language design in the future will be increasingly concerned with progressively higher levels of control and abstraction: for example the number of parameters to make a character walk are simply so great that it is not practical to animate them one by one—more powerful commands like WALK are needed to integrate the many translations and rotations of walking. These issues, like animating the dynamics of a chair falling down stairs or a vine growing on a tree are approached using a variety of dynamic modeling, simulation, and artifical intelligence approached and will be developed in more detail below in the Dynamics chapter below.

Macromind director. Autodesk animator.

Current Issues including Kinematics, Dynamics, Graftals, Flocking

The simulation of applications and scientific visualization

In the previous pages we have presented you with a view of the computer animation process couched in terms of software simulations: of drafting, of cameras, of light, of of objects, of the cel process, of the recording medium itself. In fact it would appear that everything we do in computer animation is a simulation of some process or another.

You might note that most of what we have discussed simulating has been largely confined to the processes of kinematography and graphic animation; we now focus more of our attention on the subject matter of our pictures and how their content is derived. And again, we would like to extend the reader's patience with the simulation metaphor and use it to address the issue of applications.

Several years ago it was common to make a rather finite lists of computer animation applications (medicine, entertainment, architecture, etcera). Today such a list is endless, or at best, simply the index of the Enclylopaedia Britannica. Almost everything worth being represented in a graphical representation is worth extended temportally, that is, made to change over time. And the reason is quite simple: the world around us is changing in time. Business graphics are not a static form, they are animating lines (usually one new data point per month). The heart is not a rigid shape; it is a beating cycle. Blood flows, circulations, the operation of a computer, long division done with pencil and paper: all of these involve time series events. A snapshot of the Crab Nebula might look like a gas cloud, but when you have motion tracking on the movement of its individual stars (or particles) you can discover that it is the still expanding remnent of a supernova explosion.

In general when you want to represent something on a computer youbuild a model, a simulation of it. The simulation need not be graphical or kinographic, but it may be. If ones goal is building kinographic synthetic environments, (be they quasi-real or totally abstract) then one must appreciate simulations as a way to fabricate things such as lightning, mountains, clouds, water in a pond, atmospheres, acceleration and deceleration, the movement of plant stems in the wind, the growth of a forest, or a running animal. In other words, unless you draw them directly, actions and environments require models—simulations—be they simple or complex. Conversly, to the extent ones goal is building models, kinographics provides a visual interpretation of the events. To a businessman, a row of numbers communicates a change in sales numerically, whereas a line graph communicates those same values visually. And the brain compares these two different rankings. But in more complex senarios, for example air flows in a tornado, the quantity of numbers overwealm the numerical input facilities of the sapiens, whereas the graphical presentation remains a comprehendable solution.

The two motives—working toward models where better visualization is the goal vs working toward visualization where a better model is the goal—complement and probably forever allign both classes of interests—roughtly speaking the two classes are the artists and the scientists. The artists include people who use pictures over time to depict actions and tell stories, and the scientists use scientific visualization to graphically represent concepts whose values are changing over time. The artists have value to the scientist because their kinographical skills help forge clear instrumentation; the scientists are useful to the artists because their engineering skills help forge new controls (eg a control pannel to set a walk cycle for a horse).

Scientific visualization has been around a long time although it wasn't untill the last several years that it became a fully conscious idea and blessed as a major class of activity for the scientist. In retrospect it is easy to see its origins in the calendar, the astrological zodiac, the atomic model, and so on, in fact Zajac's 1973 movie on orbiting satellites was phrased as the result of an experiment (a hypothesis test). Scientific visualization may be diagrametic: graphs, flow charts, circuit diagrams, process flows; the scientist (or businessman) seeks to spot multi-variate relationships and anomolies in the graphical displays. Or a scientific visualization may copy physical appearances: ice forming on the wings of an aircraft as it flies at different temperatures, altitudes, and attitudes. Or a visualization may combine both techniques: Color coding the ice as it accumulates on the wing to show how cold it is; adding arrows into the air flow to make it more visible (fig. 88). Similarly, data which may be measured but which likes outside the domain of our senses may be transvisualized into data we can perceive with our eyes. For example an animation of the intersection between the solar wind and the planitary magnosphere of Jupiter (fig. 89).

The introduction by Benoit Mandelbroit of fractal geometry (1977) to simulate the irregular and organic objects found in nature provided the breakthrough that propelled computer animation beyond the domain of formal geometric objects. Thinking shifted from the polygon to the problems involved with modeling larger structures: a mountain range (fig. 90), a tree (fig. 91), a waterfalls (fig. 92), or

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88. Simulation of a tornado utilizes real data from the atmosphere sampled at regular intervals. The representation includes quasi-realistic elements (the transparent white clouds) as well as diagramatic one (the arrows showing airflow).
89. Visualization of phenomia outside the range or ordinary human senses, often using real data as the basis of the image, is another important role of computer animation.
90. Much of the computer graphics community got introduced to fractals in a short film by Laurin (sp) Carpenter titled <u>Vol Libre</u> (1982), produced when he was working at Boeing (sp) and animated with the grace of a bird flying through mountains. One of its technological achievements was that the number of triangles in the polygon meshes that were calculated by the fractal algorithms changed depending upon how close the objects (mountains) were to the camera.
91. Growth simulations may be related to fractals but may also involve other processes, such as celular atomona (sp), and purely procedural approaches. Factors involved in growing a plant involve

the physics of how a character walks. These newer simulation algorithms began to incorporate dynamic physical models—simulations which utilize the forces acting on the environment, as opposted to kinematic simulation which simply model how environments behave. (By an environment we simply mean all the things that are modeled, including objects, lights, centers of gravity, the camera, ectera). These techniques make it easier to think about things like the action of ocean waves on the beach (fig. 93), flags waving in the wind (fig. 94), or the movement of clothing on the figure. Many of these simulations are better thought about in terms of voxels and practical solutions require supercomputer power (or beyond). There is a story (I don't know if it is true or not) that there is a computer somewhere that can predict five days worth of weather; the only problem is that it takes 30 days to make the calculation. The kinematic and dynamic approaches are a major component of computer animation study and are topics developed in whole chapters.

Thus simulation of what we might call "application areas" lies before us. The tip of the iceberg is already visible: expanded material properities of objects (transparency, refraction, procedural textures), widespread development of second level algorithms which orchestrate groups of objects (eg flocking, particle systems, walks), and "scientific visualizations" of the physical world (fractals, plant growth, weather, earthquakes, solar systems and beyond). One of the areas of particular interest to the computer animator is character

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how far a brach grows before it divides, how may new branches bud at each division, and the amount of rotation the new branches have to the original. These kind of formal approaches (simulations) invite instant cross discipline interaction between computer animators (who are very concerned with geometry and action) and people like biotonists (who study and classify living plants).

92. A particle system is the basis for animating this waterfall, in which the rendering is slightly abstract and the action eloquent.

93. Physical models are necessary to animate the action of waves on a beach.

94. A key frame approach to animating the action of a flag waving in the wind is tedious and at best a crude approximation; a better approach is to model the action as a series of forces and resistances, and let the computer simulate the results in a "straight ahead" approach to the problem. In a sense, the animator provides the parameters of the problem, and the simulation determines just how the flag behaves. [Locate from Jerry Weil.]

animation. It is already obvious that a specialized understanding of the sapiens structure and movement has vast applications in art as well as science, and that higher order techniques, such as artifical intelligence are required to faciliate practical direction, such as "George climb the stairs" (fig. 95). Already character animation is a topic so vast that we are defering it to a subsequent volume.

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95. The idea of goal directed simulations is to approach problems at a higher level. For example, instead of trying to animating all the joint angles of a figure as it walks on level ground, up and down inclines, or up and down stairs, the simulation employs rules which must be maintained. In the case of the walking figure these include maintaining an upright posture, ensuring foot contact with the ground, knowing the range of joint angles possible, and moving in a certain direction. The software then manipulates the joints so that these goals are maintained.