CHAPTER

1 Introduction

Computer animation, for many people, is synonymous with big-screen events such as *Star Wars*, *Toy Story*, and *Avatar*. But not all, or arguably even most, computer animation is done in Hollywood. It is not unusual for Saturday morning cartoons to be entirely computer generated. Computer games take advantage of state-of-the-art computer graphics techniques and have become a major motivating force driving research in computer animation. Real-time performance-driven computer animation has appeared at SIGGRAPH[1] and on *Sesame Street*. Desktop computer animation is now possible at a reasonable cost. Computer animation on the Web is routine. Digital simulators for training pilots, SWAT teams, and nuclear reactor operators are commonplace. The distinguishing characteristics of these various venues are the cost, the image quality desired, and the amount and type of interaction allowed. This book does not address the issues concerned with a particular venue, but it does present algorithms and techniques used to do computer animation in all of them.

Computer animation, as used here, refers to any computer-based computation used in producing images intended to create the perception of motion. The emphasis in this book is on algorithms and techniques that process three-dimensional graphical data. In general, any value that can be changed can be animated. An object's position and orientation are obvious candidates for animation, but all of the following can be animated as well: the object's shape, its shading parameters, its texture coordinates, the light source parameters, and the camera parameters.

This book is organized as follows. To lay a firm foundation for the rest of the book, Chapter 2 surveys the technical background of computer graphics relevant to computer animation. This includes the fundamental geometric transformations and associated representations of graphical data. It can be skipped by those well versed in the mathematics of the computer graphics display pipeline. Chapters 3–11 cover various computer animation algorithms and techniques: Chapters 3–5 deal with directly specifying motion (kinematics), Chapter 6 covers digitizing motion (motion capture), Chapters 7 and 8 consider physically based animation (dynamics), and Chapters 9–11 concentrate on (mostly human) figure animation. Finally, Chapter 12 surveys some modeling techniques that have been used in computer animation. The appendices provide ancillary material. Appendix A covers rendering issues that are relevant for animation, and Appendix B provides detail of the mathematics used in the text.

In considering computer animation techniques, there are basically three general approaches to motion control. The first is *artistic animation* in which the animator has the prime responsibility for crafting the motion. The foundation of artistic animation is interpolation. Various animation

[1]SIGGRAPH is the Association for Computing Machinery's (ACM) special interest group on computer graphics. The ACM is the main professional group for computer scientists.

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techniques based on interpolation are concentrated in the early chapters (Chapters 3–5). The second is *data-driven animation* in which live motion is digitized and then mapped onto graphical objects. The primary technology for data-driven animation is referred to as *motion capture* and is the topic of Chapter 6. The third is *procedural animation*, in which there is a computational model that is used to control the motion. Usually, this is in the form of setting initial conditions for some type of physical or behavioral simulation. Procedural animation is concentrated in the later chapters (Chapters 7–11).

To set the context for computer animation, it is important to understand its heritage, its history, and certain relevant concepts. The rest of this chapter discusses motion perception, the technical evolution of animation, animation production, and notable works in computer animation. It provides a grounding in computer animation as a field of endeavor.

1.1 Motion perception

A picture can quickly convey a large amount of information because the human visual system is a sophisticated information processor. It follows, then, that moving images have the potential to convey even more information in a short time. Indeed, the human visual system has evolved to provide for survival in an ever-changing world; it is designed to notice and interpret movement.

It is widely recognized that a series of images, when displayed in rapid succession, are perceived by an observer as a single moving image. This is possible because the eye–brain complex has the ability, under sufficient viewing conditions and within certain playback rates, to create a sensation of continuous imagery from such a sequence of still images. A commonly held view is that this experience is due to *persistence of vision*, whereby the eye retains a visual imprint of an image for a brief instant once the stimulus is removed. It is argued that these imprints, called *positive afterimages* of the individual stills, fill in the gaps between the images to produce the perception of a continuously changing image. Peter Roget (of *Roget's Thesaurus* fame) presented the idea of impressions of light being retained on the retina in 1824 [35]. But persistence of vision is not the same as perception of motion. Rotating a white light source fast enough will create the impression of a stationary white ring. Although this effect can be attributed to persistence of vision, the result is static. The sequential illumination of a group of lights typical of a movie theater marquee produces the illusion of a lighted object circling the signage. Motion is perceived, yet persistence of vision does not appear to be involved because no individual images are present. Recently, the causality of the (physiological) persistence of vision mechanism has been called into question and the perception of motion has been attributed to a (psychological) mechanism known as the *phi phenomenon* (as is the case in the movie marquee example given above). A related phenomenon, for example the apparent motion of a disk traveling between two flickering disks, is referred to as *beta movement* [1] [2] [13] [39].

Whatever the underlying mechanism is, the result is that in both film and video, a sequence of images can be displayed at rates fast enough to fool the eye into interpreting it as continuous imagery. When the perception of continuous imagery fails to be created, the display is said to *flicker*. In this case, the animation appears as a rapid sequence of still images to the eye–brain complex. Depending on conditions such as room lighting and viewing distance, the rate at which individual images must be played back in order to maintain the perception of continuous imagery varies. This rate is referred to as the *critical flicker frequency* [8].

While perception of motion addresses the lower limits for establishing the perception of continuous imagery, there are also upper limits to what the eye can perceive. The receptors in the eye continually sample light in the environment. The limitations on motion perception are determined, in part, by the reaction time of those sensors and by other mechanical limitations such as blinking and tracking. If an object moves too quickly with respect to the viewer, then the receptors in the eye will not be able to respond fast enough for the brain to distinguish sharply defined, individual detail; *motion blur* results [11]. In a sequence of still images, motion blur is produced by a combination of the object's speed and the time interval over which the scene is sampled. In a still camera, a fast-moving object will not blur if the shutter speed is fast enough relative to the object's speed. In computer graphics, motion blur will never result if the scene is sampled at a precise instant in time; to compute motion blur, the scene needs to be sampled over an interval of time or manipulated to appear as though it were [21] [32]. (See Appendix A.3 for a discussion of motion blur calculations.) If motion blur is not calculated, then images of a fast-moving object can appear disjointed, similar to viewing live action under the effects of a strobe light. This effect is often referred to as *strobing*. In hand-drawn animation, fast-moving objects are typically stretched in the direction of travel so that the object's images in adjacent frames overlap [49], reducing the strobing effect.

As reflected in the previous discussion, there are actually two rates of concern. One is the *playback* or *refresh* rate—the number of images per second displayed in the viewing process. The other is the *sampling* or *update* rate—the number of different images that occur per second. The playback rate is the rate related to flicker. The sampling rate determines how jerky the motion appears. For example, a television signal conforming to the National Television Standards Committee (NTSC) format displays images at a rate of roughly 30 frames per second (fps),[2] but because it is *interlaced*,[3] *fields* are played at 60 frames per second to prevent flicker under normal viewing conditions [34]. In some programs (e.g., some Saturday morning cartoons) there may be only six different images per second, with each image repeatedly displayed five times. Often, lip-sync animation is drawn *on twos* (every other frame) because drawing it *on ones* (animating it in every frame) makes it appear too hectic. Film is typically shown in movie theatres at playback rates of 24 fps (in the United States) but, to reduce the flicker, each frame is actually displayed twice (*double-shuttered*) to obtain an effective refresh rate of 48 fps. On the other hand, because an NTSC television signal is interlaced, smoother motion can be produced by sampling the scene every 60th of a second even though the complete frames are only played back at 30 fps [8]. Computer displays are typically progressive scan (*noninterlaced*) devices with refresh rates above 70 fps [34]. See Appendix B.10 for some details concerning various film and video formats.

The display and perception of animation using a sequence of still images imposes certain requirements on how those images are computed and played effectively. Understanding the operation, limits, and trade-offs of the human visual system are essential when making intelligent decisions about designing any type of visual and auditory content, including computer animation.

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[2] More accurately, the format for broadcast television system, established by the NTSC, specifies a frame rate of 29.97 fps [29].

[3] An *interlaced* display is one in which a frame is divided into two *fields*. Each field consists of odd or even numbered scan-lines. The odd and even fields are displayed in alternate scans of the display device [8].

1.2 The heritage of animation

In the most general sense, *animate*[4] means “give life to” and includes live-action puppetry such as that found on *Sesame Street* and the use of electromechanical devices to move puppets, such as *animatronics*. History is replete with attempts to bring objects to life. This history is a combination of myth, deception, entertainment, science, and medicine. Many of the references to animation are in the form of stories about conjuring a life force into some humanoid form: from Pygmalion to Prometheus to Wagner’s homunculus in Goethe’s *Faust* to Shelley’s Dr. Frankenstein. Some of the history is about trying to create mechanical devices that mimic certain human activity: from Jacque Vaucanson’s mechanical flute player, drummer, and defecating duck in the 1730s to Wolfgang von Kempelen’s chess player in 1769 to Pierre Jaquet-Droz’s writing automaton of 1774 to the electromechanical humanoid robots (*animatronics*) popular today. The early mechanisms from the 1700s and 1800s were set in the milieu of scientific debate over the mechanistic nature of the human body (e.g., *L’Homme Machine*, translated as *Man a Machine*, was written by Julien Offray de La Mettrie in 1747 and was quite controversial). This activity in humanoid mechanical devices was propelled by a confluence of talents contributed by magicians, clock makers, philosophers, scientists, artists, anatomists, glove makers, and surgeons (see Gaby Wood’s book for an entertaining survey on the quest for mechanical life [50]). Here, however, the focus is on devices that use a sequence of individual still images to create the effect of a single moving image, because these devices have a closer relationship to hand-drawn animation.

1.2.1 Early devices

Persistence of vision and the ability to interpret a series of stills as a moving image were actively investigated in the 1800s [5], well before the film camera was invented. The recognition and subsequent investigation of this effect led to a variety of devices intended as parlor toys [23] [38]. Perhaps the simplest of these early devices is the *thaumatrope*, a flat disk with images drawn on both sides with two strings connected opposite each other on the rim of the disk (see Figure 1.1). The disk could be quickly flipped back and forth by twirling the strings. When flipped rapidly enough, the two images appear to be superimposed. The classic example uses the image of a bird on one side and the image of a birdcage on the other; the rotating disk visually places the bird inside the birdcage. An equally primitive technique is the *flip book*, a tablet of paper with an individual drawing on each page. When the pages are flipped rapidly, the viewer has the impression of motion.

One of the most well known early animation devices is the *zoetrope*, or wheel of life. The zoetrope has a short fat cylinder that rotates on its axis of symmetry. Around the inside of the cylinder is a sequence of drawings, each one slightly different from the ones next to it. The cylinder has long vertical slits cut into its side between each adjacent pair of images so that when it is spun on its axis each slit allows the eye to see the image on the opposite wall of the cylinder (see Figure 1.2). The sequence of slits passing in front of the eye as the cylinder is spun on its axis presents a sequence of images to the eye, creating the illusion of motion.

[4]A more restricted definition of *animation*, also found in the literature, requires the use of a sequence of stills to create the visual impression of motion. The restricted definition does not admit techniques such as animatronics or shadow puppets under the rubric animation.

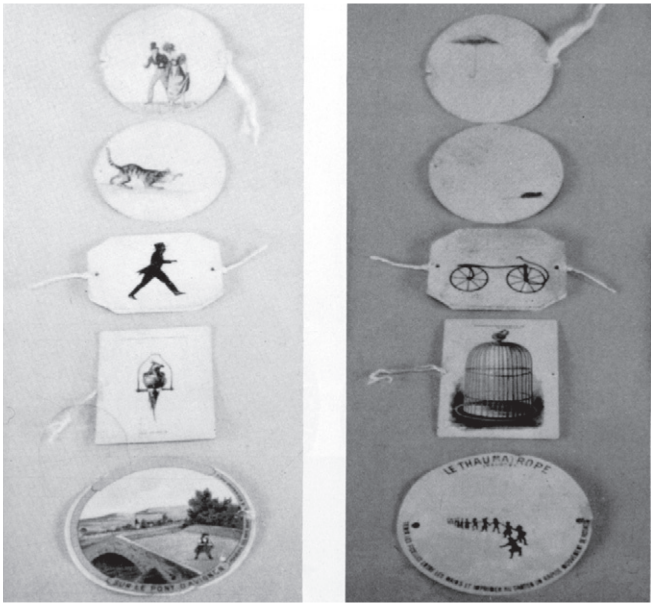

FIGURE 1.1

A thaumatrope.

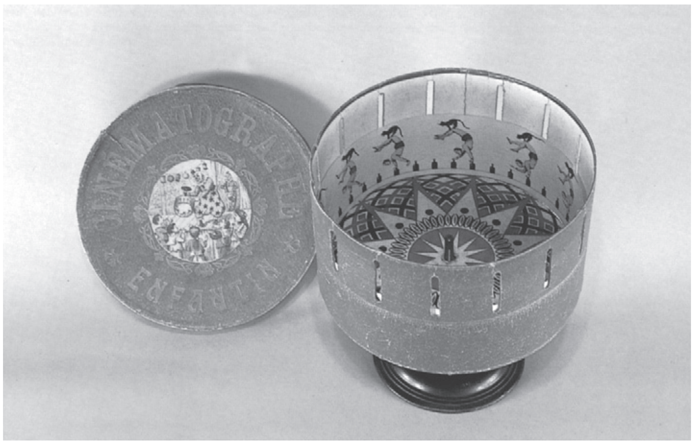

FIGURE 1.2

A zoetrope.

Related gizmos that use a rotating mechanism to present a sequence of stills to the viewer are the *phenakistoscope* and the *praxinoscope*. The phenakistoscope also uses a series of rotating slots to present a sequence of images to the viewer by positioning two disks rotating in unison on an axis; one disk has slits, and the other contains images facing the slits. One sights along the axis of rotation so the slits pass in front of the eye, which can thus view a sequence of images from the other disk.

The praxinoscope uses a cylindrical arrangement of rotating mirrors inside a large cylinder of images facing the mirrors. The mirrors are angled so that, as the cylinders rotate in unison, each image is successively reflected to the observer.

Just before the turn of the century, the moving image began making its way on stage. The *magic lantern* (an image projector powered by candle or lamp) and shadow puppets became popular theater entertainment [3]. On the educational front, Etienne-Jules Marey [27] and Eadweard Muybridge [30] [31] investigated the motions of humans and animals. To show image sequences during his lectures, Muybridge invented the *zoopraxinoscope*, a projection device also based on rotating slotted disks. Then, in 1891, the seed of a revolution was planted: Thomas Edison invented the motion picture viewer (the *kinetoscope*), giving birth to a new industry [38].

1.2.2 The early days of "conventional" animation

Animation in America exploded in the twentieth century in the form of filming hand-drawn, two-dimensional images (referred to here also as *conventional* or *traditional* animation). Studying the early days of conventional animation is interesting in itself [26] [38] [44] [45], but the purpose of this overview is to provide an appreciation of the technological advances that drove the progress of animation during the early years.

Following Edison's kinetoscope, there were several rapid developments in film technology. One of the most notable developments was the motion picture projector by the Lumiere brothers, Auguste and Louis, in France. They are credited with the first commercial, public screening of film in Paris on December 28, 1895. They called their device the *cinematograph*. It is a camera that could both project and develop film. They used it to film everyday events including a train coming into a train station; this footage, when shown to the audience, sent everyone scrambling for cover. It was also used for aerial photography (years before the airplane took to the skies).

The earliest use of a camera to make lifeless things appear to move occurred in 1896 by Georges Méliès. Méliès used simple camera tricks such as multiple exposures and stop-motion techniques to make objects appear, disappear, and change shape [18] [47]. His best known trick film is *A Trip to the Moon* (1902). One of the earliest pioneers in film animation was J. Stuart Blackton, an American who animated "smoke" in a scene in 1900, ushering in the field of *visual effects*. Blackton is credited with creating the first animated cartoon, *Humorous Phases of Funny Faces* (1906), by drawing and erasing on a chalkboard between takes. Emile Cohl, a Frenchman, produced several vignettes including *Fantasmagorie* (1908), which is considered to be the first fully animated film ever made. The American Winsor McCay is the first celebrated animator, best known for his works *Little Nemo* (1911) and *Gertie the Dinosaur* (1914). McCay is considered by many to have produced the first popular animations [26].

Like many of the early animators, McCay was an accomplished newspaper cartoonist. He redrew each complete image on rice paper mounted on cardboard and then filmed them individually. He was also the first to experiment with color in animation. Much of his early work was incorporated into vaudeville acts in which he "interacted" with an animated character on a screen. Similarly, early cartoons often incorporated live action with animated characters. To appreciate the impact of such a popular entertainment format, keep in mind the relative naïveté of audiences at the time; they had no idea how film worked, much less what hand-drawn animation was. As Arthur C. Clarke stated about sufficiently advanced technology, it must have been indistinguishable from magic.

The first major technical developments in the animation process can be traced to the efforts of John Bray, one of the first to recognize that patenting aspects of the animation process would result in a competitive advantage [26]. Starting in 1910, his work laid the foundation for conventional animation as it exists today. Earl Hurd, who joined forces with Bray in 1914, patented the use of translucent *cels*[5] in the compositing of multiple layers of drawings into a final image and also patented gray scale drawings as opposed to black and white. Later developments by Bray and others enhanced the overlay idea to include a peg system for registration and the drawing of the background on long sheets of paper so that *panning* (translating the background relative to the camera, perpendicular to the view direction) could be performed more easily. Out of Bray's studio came Max Fleischer (Betty Boop), Paul Terry (Terrytoons), George Stallings (Tom and Jerry), and Walter Lantz (Woody Woodpecker). In 1915, Fleischer patented *rotoscoping* (drawing images on cells by tracing over previously recorded live action). Several years later, in 1920, Bray experimented with color in the short *The Debut of Thomas Cat*.

While the technology was advancing, animation as an art form was still struggling. The first animated character with an identifiable personality was Felix the Cat, drawn by Otto Messmer of Pat Sullivan's studio [26]. Felix was the most popular and most financially successful cartoon of the mid-1920s. In the late 1920s, however, new forces had to be reckoned with: sound and Walt Disney.

1.2.3 Disney

Walt Disney was, of course, the overpowering force in the history of conventional animation. Not only did his studio contribute several technical innovations, but Disney, more than anyone else, advanced animation as an art form [45]. Disney's innovations in animation technology included the use of a storyboard to review the story and pencil sketches to review motion. In addition, he pioneered the use of sound and color in animation (although he was not the first to use color). Disney also studied live-action sequences to create more realistic motion in his films. When he used sound for the first time in *Steamboat Willie* (1928), he gained an advantage over his competitors.

One of the most significant technical innovations of the Disney studio was the development of the multiplane camera [26] [44]. The multiplane camera consists of a camera mounted above multiple planes, each of which holds an animation cell. Each of the planes can move in six directions (right, left, up, down, in, out), and the camera can move closer and farther away (see Figure 1.3).

Multiplane camera animation is more powerful than one might think. By moving the camera closer to the planes while the planes are used to move foreground images out to the sides, a more effective zoom can be performed. Moving multiple planes at different rates can produce the *parallax effect*, which is the visual effect of closer objects apparently moving faster across the field of view than objects farther away, as an observer's view pans across an environment. This is very effective in creating the illusion of depth and an enhanced sensation of three dimensions. Keeping the camera lens open during movement can produce several additional effects: figures can be extruded into shapes of higher dimension, depth cues can be incorporated into an image by blurring the figures on more distant cels, and a blurred image of a moving object can be produced.

[5] Cel is short for *celluloid*, which was the original material used in making the translucent layers. Currently, cels are made from acetate.

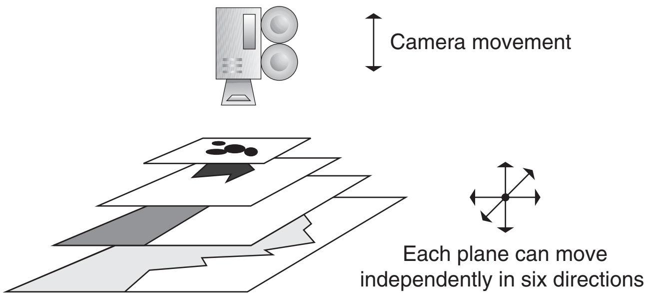

FIGURE 1.3

Directional range of the multiplane camera, inside of which the image is optically composited.

With regard to the art of animation, Disney perfected the ability to impart unique, endearing personalities in his characters, such as those exemplified in Mickey Mouse, Pluto, Goofy, the Three Little Pigs, and the Seven Dwarfs [44] [45]. He promoted the idea that the mind of the character was the driving force of the action and that a key to believable animated motion was the analysis of real-life motion. He also developed mood pieces, for example, *Skeleton Dance* (1929) and *Fantasia* (1940).

1.2.4 Contributions of others

The 1930s saw the proliferation of animation studios, among them Fleischer, Iwerks, Van Beuren, Universal Pictures, Paramount, MGM, and Warner Brothers. The technological advances that are of concern here were mostly complete by this period. The differences between, and contributions of, the various studios have to do more with the artistic aspects of animation than with the technology involved in producing animation [26]. Many of the notable animators in these studios were graduates of Disney's or Bray's studio. Among the most recognizable names are Ub Iwerks, George Stallings, Max Fleischer, Bill Nolan, Chuck Jones, Paul Terry, and Walter Lantz.

1.2.5 Other media for animation

The rich heritage of hand-drawn animation in the United States makes it natural to consider it the precursor to computer animation, which also has strong roots in the United States. However, computer animation has a close relationship to other animation techniques as well.

A good comparison can be made between computer animation and some of the stop-motion techniques, such as clay and puppet animation. Typically, in three-dimensional computer animation, one of the first steps is the object modeling process. The models are then manipulated to create the three-dimensional scenes that are rendered to produce the images of the animation. In much the same way, clay and puppet stop-motion animation use three-dimensional figures that are built and then animated in separate, well-defined stages [23]. Once the physical three-dimensional figures are created, they are used to lay out a three-dimensional environment. A camera is positioned to view the environment and record an image. One or more of the figures are manipulated, and the camera may be repositioned. The camera records another image of the scene. The figures are manipulated again, another image is taken of the scene, and the process is repeated to produce the animated sequence.

Willis O'Brien of *King Kong* fame is generally considered the dean of this type of stop-motion animation. His understudy, who went on to create an impressive body of work in his own right, was Ray Harryhausen (*Mighty Joe Young*, *Jason and the Argonauts*, and many more). More recent impressive examples of three-dimensional stop-motion animation are Nick Park's *Wallace and Gromit* series and *Chicken Run* and Tim Burton's projects such as *The Nightmare Before Christmas*, *James and the Giant Peach*, *Corpse Bride*, and *Alice in Wonderland*.

Because of computer animation's close association with video technology, it has also been associated with video art, which depends largely on the analog manipulation of the video signal in producing effects such as colorization and warping [12]. Because creating video art is inherently a two-dimensional process, the relationship is viewed mainly in the context of computer animation post-production techniques. Even this connection has faded because the popularity of recording computer animation by digital means has eliminated most analog processing.

1.3 Animation production

Although producing a final animated film is not the subject of this book, the production process merits some discussion in order to establish the context in which an animator works. It is useful for technical animators to have some familiarity with how a piece of animation is broken into parts and how a finished piece is produced. Much of this is taken directly from conventional animation and is directly applicable to any type of animation.

A piece of animation is usually discussed using a four-level hierarchy, although the specific naming convention for the levels may vary.[6] Here, the overall animation—the entire project—is referred to as the *production*. Typically, productions are broken into major parts referred to as *sequences*. A sequence is a major episode and is usually identified by an associated staging area; a production usually consists of one to a dozen sequences. A sequence is broken down into one or more *shots*; each shot is the recording of the action from a single point of view. A shot is broken down into the individual *frames* of film. A frame is a single recorded image. This results in the hierarchy shown in Figure 1.4.

Several steps are required to successfully plan and carry out the production of a piece of animation [23] [44]. Animation is a trial-and-error process that involves feedback from one step to previous steps

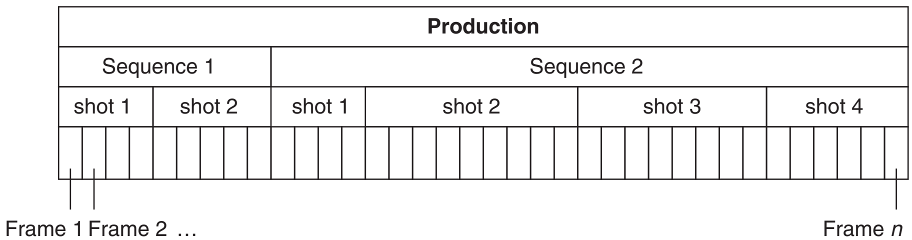

FIGURE 1.4

Sample hierarchy of a simple animation production.

[6]Live-action film tends to use a five-level hierarchy: film, sequence, scene, shot, and frame [9]. Here, the terminology, which is often used in feature-length computer animation, is presented.

and usually demands several iterations through multiple steps at various times. Even so, the production of animation typically follows a standard pattern. First, a *preliminary story* is decided on, including a *script*. A *storyboard* is developed that lays out the action scenes by sketching representative frames. The frames are often accompanied by text that sketches out the action taking place. This is used to present, review, and critique the action as well as to examine character development.

A model sheet is developed that consists of a number of drawings for each figure in various poses and is used to ensure that each figure's appearance is consistent as it is repeatedly drawn during the animation process. The exposure sheet records information for each frame such as sound track cues, camera moves, and compositing elements. The *route sheet* records the statistics and responsibility for each scene.

An *animatic*, or *story reel*, may be produced in which the storyboard frames are recorded, each for as long as the sequence it represents, thus creating a rough review of the timing. Often, a *scratch track*, or *rough sound track*, is built at the same time the storyboard is being developed and is included in the animatic. Once the storyboard has been decided on (see Figure 1.5), the *detailed story* is worked out to identify the actions in more detail. *Key frames* (also known as *extremes*) are then identified and produced by master animators to aid in confirmation of timing, character development, and image quality. Associate and assistant animators are responsible for producing the frames between the keys; this is called *in-betweening*. *Test shots*, short sequences rendered in full color, are used to test the rendering and motions. To completely check the motion, a *pencil test* may be shot, which is a full-motion rendering of an extended sequence using low-quality images such as pencil sketches. Problems identified in the test shots and pencil tests may require reworking of the key frames, detailed story, or even the storyboard.

Inking refers to the process of transferring the penciled frames to cels. *Opaquing*, also called *painting*, is the application of color to these cels.

1.3.1 Principles of animation

To study various techniques and algorithms used in computer animation, it is useful to first understand their relationship to the animation principles used in hand-drawn animation. In an article by Lasseter [22], the principles of animation, articulated by some of the original Disney animators [45], are related to techniques commonly used in computer animation. The principles are squash and stretch, timing, secondary action, slow in and slow out, arcs, follow through and overlapping action, exaggeration, appeal, anticipation, staging, solid drawing, and straight ahead and pose to pose. Lasseter is a conventionally trained animator who worked at Disney before going to Pixar. At Pixar, he was responsible for many celebrated computer animations including *Tin Toy* that, in 1989, was the first computer animation to win an Academy Award. Whereas Lasseter discusses each principle in terms of how it might be implemented using computer animation techniques, the principles are organized here according to the type of motion quality they contribute to in a significant way. Because several principles relate to multiple qualities, some principles appear under more than one heading.

Simulating physics

Squash and stretch, *timing*, *secondary action*, *slow in and slow out*, and *arcs* establish the physical basis of objects in the scene. A given object possesses some degree of rigidity and should appear to have some amount of mass. This is reflected in the distortion (squash and stretch) of its shape during an

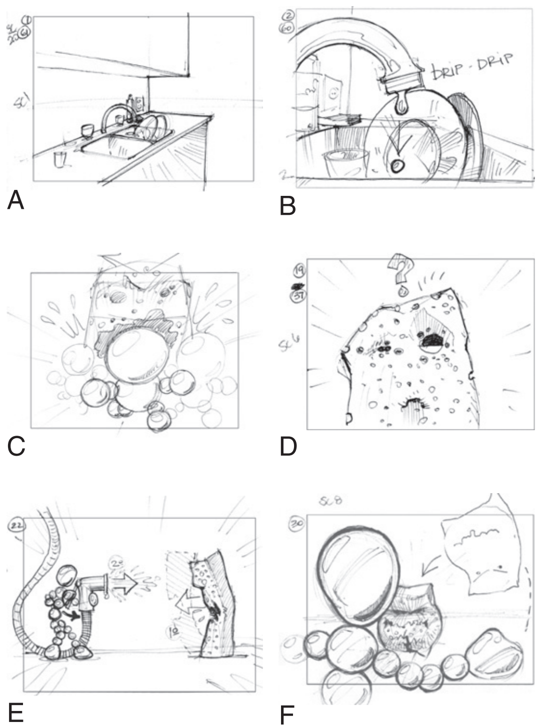

FIGURE 1.5

Sample panels from a storyboard. (a) Establishing shot: overview of the background introduces the place where the action takes place. (b) Extreme close-up: the action is shown in detail helping the viewer to get familiar with the main characters and objects. (c) Low angle: the camera position and the action happen in the same camera direction increasing the dramatic feeling of the scene. (d) POV (point of view): shows the viewer what the character would be seeing, which helps to better understand the reaction to the action. (e) Wide shot: shows the whole action making the viewer understand the motivation, the action, and the consequences all at once. (f) OTS (over the shoulder): the camera looks to one character, or action, from just behind and over the shoulder of another character to get the viewer involved with the action. (Images courtesy of Beth Albright and Iuri Lioi.)

action, especially a collision. The animation must support these notions consistently for a given object throughout the animation. Timing has to do with how actions are spaced according to the weight, size, and personality of an object or character and, in part, with the physics of movement as well as the artistic aspects of the animation. Secondary action supports the main action, possibly supplying physically based reactions to an action that just occurred. Slow in and slow out and arcs are concerned with how things move through space. Objects slow in and slow out of poses. When speaking of the actions involved, objects are said to “ease in” and “ease out.” Such speed variations model inertia, friction, and viscosity. Objects, because of the physical laws of nature such as gravity, usually move not in straight lines but rather in arcs.

Designing aesthetically pleasing actions

Appeal, *solid drawing*, and *follow through/overlapping action* are principles that address the aesthetic design of an action or action sequence. To keep the audience's attention, the animator needs to make it enjoyable to watch (appeal). In addition, actions should flow into one another (follow through/overlapping action) to make the entire shot appear to continually evolve instead of looking like disjointed movements. Solid drawing refers to making the character look pliable and not stiff or wooden. Squash and stretch can also be used in this regard. Secondary actions and timing considerations also play a role in designing pleasing motion.

Effectively presenting action

Often the animator needs to employ *exaggeration* so a motion cannot be missed or so it makes a point (Tex Avery is well known for this type of conventional animation). *Anticipation* and *staging* concern how an action is presented to the audience. Anticipation dictates that an upcoming action is set up so that the audience knows it (or something) is coming. Staging expands on this notion of presenting an action so that it is not missed by the audience. *Timing* is also involved in effective presentation to the extent that an action has to be given the appropriate duration for the intended effect to reach the audience. *Secondary action* can also be used to create an effective presentation of an action.

Production technique

Straight ahead versus *pose to pose* concerns how a motion is created. Straight ahead refers to progressing from a starting point and developing the motion continually along the way. Physically based animation could be considered a form of straight ahead processing. Pose to pose, the typical approach in conventional animation, refers to identifying key frames and then interpolating the intermediate frames, an approach the computer is particularly good at.

1.3.2 Principles of filmmaking

Basic principles of filmmaking are worth reviewing in order to get a sense of how effective imagery is constructed. Several of the basic principles are listed in the following sections, although more complete references should be consulted by the interested reader (e.g., [28]). Some of the following principals are guidelines that should be followed when composing a single image; others are options of how to present the action.

Three-point lighting

There is a standard set of three lights that are used to illuminate the central figure in a scene. These are the *key light*, the *fill light*, and the *rim light*. The key light is often positioned up and to the side of the camera, pointing directly at the central figure. This focuses the observer's attention on what is important. The rim light is positioned behind the central figure and serves to highlight the rim, thus outlining the figure and making the figure stand out from the background. The fill light is a flood light typically positioned below the camera that fills the figure with a soft light bringing out other details in the figure's appearance. See Figure 1.6 (Color Plate 1) for an example.

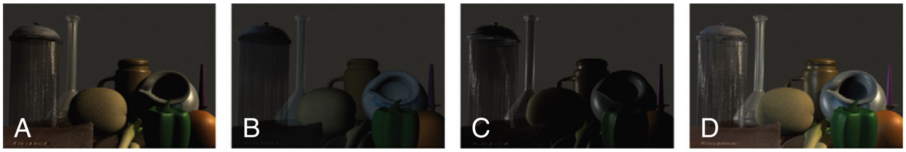

FIGURE 1.6

Three-point lighting example: (a) Key light: A single spot light is placed at 45 degrees from the top-right of the frame. This light has the highest intensity in the setup and is responsible for the cast shadows of the objects. (b) Fill light: A blue fill light from the front and right of the object is used to illuminate the dark areas created by the key light. This light is less intense and does not cast shadows or highlights on the objects. (c) Rim light: Multiple lights are placed opposite the direction of the key light. They highlight the edges, which are otherwise in shadow. These highlights help separate the objects from the background as well as from other overlapping objects in the scene. (d) All lights: This is the final lighting set up—a combination of key, fill, and rim lights. The scene is rendered with ray tracing, generating reflections on selective surfaces. (Images courtesy of Sucheta Bhatawadekar, ACCAD.)

180 rule

When filming a line of action, for example the conversation between two figures, it is common to show each figure in isolation during the action. The camera is positioned in front of a figure but a little off to the side. The 180 degree rule states that when showing the two figures, one after the other, in isolation, the camera should stay on the same side of the line of action. Thus, the camera's orientation should stay within the 180 degrees that is on one side of the line between the figures.

Rule of thirds

The rule of thirds says that the interesting places to place an object in an image are one-third along the way, either side-to-side or up-and-down or both. In particular, don't center your subject in the image and don't put your subject at the edge of the image.

Types of shots

Types of camera shots are categorized based on the distance from the camera to the subject and the angle at which the shot is taken. The distance-based shots are *extreme long range*, *long range*, *medium range* or *bust shot*, *close-up*, and *extreme close-up*. Which type of shot to use depends on the amount and location of detail that is to be shown and how much environmental context is to be included in the shot.

A *low angle shot*, meaning the camera is low shooting up at the subject, imparts a feeling of power or dominance to the subject. Conversely, a *high angle shot*, in which the camera shoots down on the subject, presents a feeling that the subject is insignificant or subordinate.

Tilt

Tilting the camera (rotating the camera about its view direction) can convey a sense of urgency, strangeness, or fear to the shot.

Framing

Framing refers to allowing enough room in the image for the action being captured. In a relatively static view, allow enough room so the subject does not fill the frame (unless there is a reason to do so). Allow enough room for motion. If your subject is walking, frame the motion so there is room in front of the subject so the subject does not appear to be walking out of the frame.

Focus the viewer's attention

Draw the viewer's attention to what's important in the image. Use color, lighting, movement, focus, etc., to direct the attention of the viewer to what you want the viewer to see. For example, the eye will naturally follow converging lines, the gaze of figures in the image, a progression from dark to light or dark to bright, and an identifiable path in the image.

1.3.3 Sound

Sound is an integral part of almost all animation, whether it's hand-drawn, computer-based, or stop-motion [23] [26]. Up through the 1920s, the early "silent films" were played in theaters with live mood music accompaniment. That changed as sound recording technology was developed for film and, later, for video.

Audio recording techniques had been around for 30 years by the time moving images were first recorded on film. It took another 30 years to develop techniques for playing a sound track in sync with recorded action. Since then, various formats have been developed for film sound tracks. Most formats record the audio on the same medium that records the images. In most of the various formats for film, for example, audio is recorded along the side of the images or between the sprocket holes in one to six tracks. Early formats used optical or magnetic analog tracks for sound, but more recent formats digitally print the sound track on the film. By recording the audio on the same stock as the film, the timing between the imagery and the audio is physically enforced by the structure of the recording technology. In some formats, a separate medium, such as a CD, is used to hold the audio. This allows more audio to be recorded, but creates a synchronization issue during playback. In the case of video, audio tracks are recorded alongside the tracks used to encode the video signal.

In the early film and video formats, audio was recorded as a low bandwidth analog signal resulting in very low-quality sound. Today's film and video technology acknowledges the importance of sound and provides multiple, high-quality digital audio tracks. Sound has four roles in a production: voice, body sounds, special effects, and background music.

In live action, voice is recorded with the action because of timing considerations while most of the other sounds are added in a post-processing phase. In animation, voices are recorded first and the animation made to sync with it. In addition, recording visuals of the voice talent during the audio recording can be used to guide the animators as they create the facial expressions and body language that accompanies the speech.

Nonspeech sounds made by the actors, such as rustling of clothes, footsteps, and objects being handled, are called body sounds. The recorded body sounds are usually replaced by synthesized sounds, called *foley*, for purposes of artistic control. These synthesized sounds must be synced with the motions of the actors. The people responsible for creating these sounds are called *foley artists*.

Special effects, such as door slams and the revving of car engines, must also be synced with the action, but with lesser precision than voice and foley sounds.

Recording background and mood music can be added after the fact and usually require no precise timing with the action. All the sounds other than voice are added after the live action or animation is recorded.

1.4 Computer animation production

Computer animation production has borrowed most of the ideas from conventional animation production, including the use of a storyboard, test shots, and pencil testing. The storyboard has translated directly to computer animation production, although it may be done on-line. It still holds the same functional place in the animation process and is an important component in planning animation. The use of key frames, and interpolating between them, has become a fundamental technique in computer animation.

While computer animation has borrowed the production approaches of conventional animation, there are significant differences between how computer animation and conventional animation create an individual frame of the animation. In computer animation, there is usually a strict distinction among creating the models; creating a layout of the models including camera positioning and lighting; specifying the motion of the models, lights, and camera; and the rendering process applied to those models. This allows for reusing models and lighting setups. In conventional animation, all of these processes happen simultaneously as each drawing is created; the only exception is the possible reuse of backgrounds, for example, with the multilayer approach.

The two main evaluation tools of conventional animation, test shots and pencil tests, have counterparts in computer animation. A speed/quality trade-off can be made in several stages of creating a frame of computer animation: model building, lighting, motion control, and rendering. By using high-quality techniques in only one or two of these stages, that aspect of the presentation can be quickly checked in a cost-effective manner. A test shot in computer animation is produced by a high-quality rendering of a highly detailed model to see a single frame, a short sequence of frames of the final product, or every *n*th frame of a longer sequence from the final animation. The equivalent of a pencil test can be performed by simplifying the sophistication of the models used, by using low-quality and/or low-resolution renderings, by eliminating all but the most important lights, or by using simplified motion.

Often, it is useful to have several representations of each model available at varying levels of detail. For example, placeholder cubes can be rendered to present the gross motion of rigid bodies in space and to see spatial and temporal relationships among objects. "Solids of revolution" objects (objects created by rotating a silhouette edge at certain intervals around an axis and then defining planar surfaces to fill the space between these silhouette slices) lend themselves quite well to multiple levels of detail for a given model based on the number of slices used. Texture maps and displacement maps can be disabled until the final renderings.

To simplify motion, articulated figures[7] can be kept in key poses as they navigate through an environment in order to avoid interpolation or inverse kinematics. Collision detection and response can be selectively "turned off" when not central to the effect created by the sequence. Complex effects such as smoke and water can be removed or represented by simple geometric shapes during testing.

[7] *Articulated figures* are models consisting of rigid segments usually connected together in a tree-like structure; the connections are revolute or prismatic joints, allowing a segment to rotate or translate relative to the segment to which it is connected.

Many aspects of the rendering can be selectively turned on or off to provide great flexibility in giving the animator clues to the finished product's quality without committing to the full computations required in the final presentation. Often, the resulting animation can be computed in real time for very effective motion testing before committing to a full anti-aliased, transparent, texture-mapped rendering. Wire frame rendering of objects can sometimes provide sufficient visual cues to be used in testing. Shadows, smooth shading, texture maps, environmental maps, specular reflection, and solid texturing are options the animator can use for a given run of the rendering program.

Even in finished pieces of commercial animation it is common practice to take computational shortcuts when they do not affect the quality of the final product. For example, the animator can select which objects can shadow which other objects in the scene. In addition to being a compositional issue, selective shadowing saves time over a more robust approach in which every object can shadow every other object. In animation, environmental mapping is commonly used instead of ray tracing; photorealistic rendering is typically avoided.

Computer animation is well suited for producing the equivalent of test shots and pencil tests. In fact, because the quality of the separate stages of computer animation can be independently controlled, it can be argued that it is even better suited for these evaluation techniques than conventional animation.

1.4.1 Computer animation production tasks

While motion control is the primary subject of this book, it is worth noting that motion control is only one aspect of the effort required to produce computer animation. The other tasks (and the other talents) that are integral to the final product should not be overlooked. As previously mentioned, producing quality animation is a trial-and-error iterative process wherein performing one task may require rethinking one or more previously completed tasks. Even so, these tasks can be laid out in an approximate chronological order according to the way they are typically encountered. The order presented here summarizes an article that describes the system used to produce Pixar's *Toy Story* [16]. See Figure 1.7.

- The *Story Department* translates the verbal into the visual. The screenplay enters the Story Department, the storyboard is developed, and the story reel leaves. These visuals then go to the Art Department.
- The *Art Department*, working from the storyboard, creates the designs and color studies for the film, including detailed model descriptions and lighting scenarios. The Art Department develops a consistent look to be used in the imagery. This look guides the Modeling, Layout, and Shading Departments.
- The *Modeling Department* creates the characters and the world in which they live. Every brick and stick to appear in the film must be handcrafted. Often, figures with jointed appendages, or other models with characteristic motion, are created as parameterized models. Parameters that control standard movements of the figure are defined. This facilitates the ability of animators to *stay on the model*, ensuring that the animation remains consistent with the concept of the model. The models are given to Layout and Shading.
- On one path between the Modeling Department and Lighting Department lies the *Shading Department*. Shading must translate the attributes of the object that relate to its visual appearance into texture maps, displacement shaders, and lighting models. Relevant attributes include the

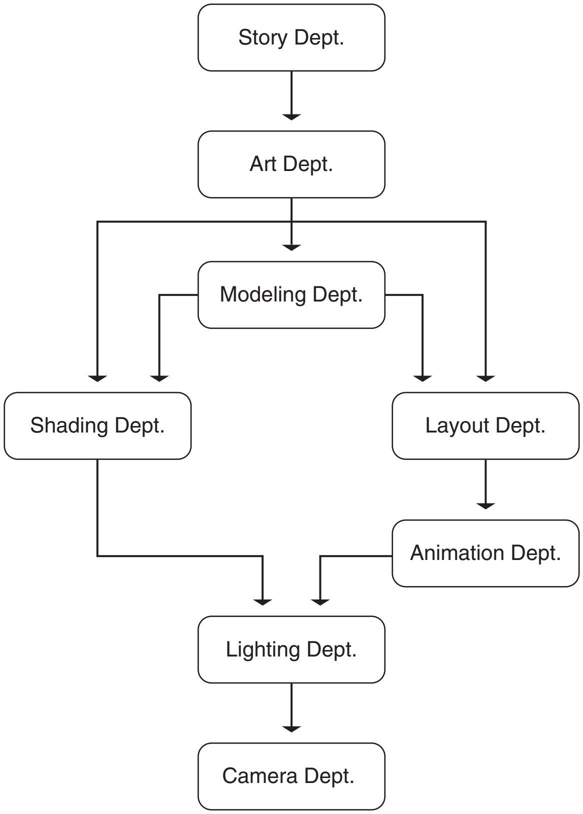

FIGURE 1.7

Computer animation production pipeline.

material the object is made of, its age, and its condition. Much of the effective appearance of an object comes not from its shape but from shading—the visual qualities of its surface.

- On the other path between Modeling and Lighting lies the *Layout Department*, followed by the Animation Department. Layout is responsible for taking the film from two dimensions to three dimensions. To ensure good flow, Layout implements proper *staging* (designing the space for the action to take place in) and *blocking* (planning out the general movements of the actors and camera). This guides the Animation Department.
- Working from audio, the story, and the blocking and staging produced by Layout, the *Animation Department* is responsible for bringing the characters to life. As mentioned above, complex figures are often parameterized by the Model Department so that a character's basic movements (e.g., smiling, taking a step) have already been defined. Animation uses these motions as well as creating the subtler gestures and movements necessary for the "actor" to effectively carry out the scene.
- The *Lighting Department* assigns to each sequence a team that is responsible for translating the Art Department's vision into digital reality. At this point the animation and camera placement

have been done. Key lights are set to establish the basic lighting environment. Subtler lighting particular to an individual shot refines this in order to establish the correct mood and bring focus to the action.

- The *Camera Department* is responsible for actually rendering the frames. During *Toy Story*, Pixar used a dedicated array of hundreds of processors called the *Render Farm*. The term render farm is now commonly used to refer to any such collection of processors for image rendering.

1.4.2 Digital editing

A revolution swept the film and video industries in the 1990s: the digital representation of images. Even if computer graphics and digital effects are not a consideration in the production process, it has become commonplace to store program elements in digital form instead of using the analog film and videotape formats. Digital representations have the advantage of being able to be copied with no image degradation. So, even if the material was originally recorded using analog means, it is often cost-effective to transcribe the images to digital image store. And, of course, once the material is in digital form, digital manipulation of the images is a natural capability to incorporate in any system.

In the old days . . .

The most useful and fundamental digital image manipulation capability is that of editing sequences of images together to create a new presentation. Originally, film sequences were edited together by physically cutting and splicing tape. This is an example of *nonlinear editing*, in which sequences can be inserted in any order at any time to assemble the final presentation. However, splicing is a time-consuming process, and making changes in the presentation or trying different alternatives can place a heavy burden on the stock material as well.

Electronic editing[8] allows the manipulation of images as electronic signals rather than using a physical process. The standard configuration uses two source videotape players, a switching box, and an output videotape recorder. More advanced configurations include a character generator (text overlays) and special effects generator (wipes, fades, etc.) on the input side, and the switching box is replaced by an editing station (see Figure 1.8). The two source tapes are searched to locate the initial desired sequence; the tape deck on which it is found is selected for recording on the output deck and the sequence is recorded. The tapes are then searched to locate the next segment, the deck is selected for input, and the segment is recorded on the output tape. This continues until the new composite sequence has been created on the output tape. The use of two source tapes allows multiple sources to be more easily integrated into the final program. Because the output is assembled in sequential order, this is referred to as *linear editing*. The linear assembly of the output is considered the main drawback of this technique. Electronic editing also has the drawback that the material is copied in the editing process, introducing some image degradation. Because the output tape is commonly used to master the tapes that are sent out to be viewed, these tapes are already third generation. Another drawback is the amount of wear on the source material as the source tapes are repeatedly played and rewound as the next desired sequence is searched for. If different output versions are required (called

[8]To simplify the discussion and make it more relevant to the capabilities of the personal computer, the discussion here focuses on video editing, although much of it is directly applicable to digital film editing, except that film standards require much higher resolution and therefore more expensive equipment.

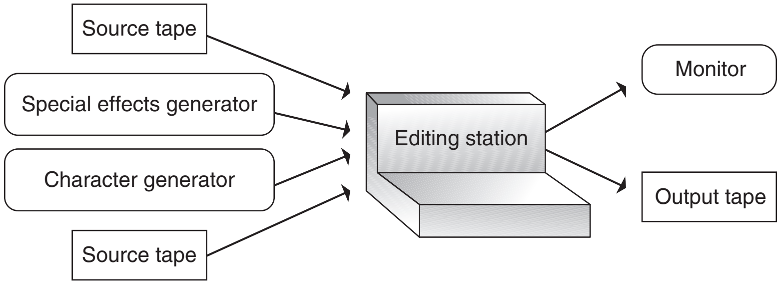

FIGURE 1.8

Linear editing system.

versioning), the source material will be subjected to even more wear and tear because the source material has to undergo more handling as it is processed for multiple purposes.

Often, to facilitate the final assemblage of the output sequence and avoid excessive wear of the original source material, copies of the source material are used in a preprocessing stage in which the final edits are determined. This is called *off-line editing*. The result of this stage is an *edit decision list* (EDL), which is a final list of the edits that need to be made to assemble the final piece. The EDL is then passed to the *on-line editing* stage, which uses the original source material to make the edits and create the finished piece. This process is referred to as *conforming*.

To keep track of edit locations, control track pulses can be incorporated onto the tape used to assemble the 30 fps NTSC video signal. Simple editing systems count the pulses, and this is called *control track editing*. However, the continual shuffling of the tape back and forth during the play and rewind of the editing process can result in the editing unit losing count of the pulses. This is something the operator must be aware of and take into account. In addition, because the edit counts are relative to the current tape location, the edit locations are lost when the editing station is turned off.

The Society of Motion Picture and Television Engineers time code is an absolute eight-digit tag on each frame in the form of HHMMSSFF, where HH is the hour, MM is the minute, SS is the second, and FF is the frame number. This tag is calculated from the beginning of the sequence. This allows an editing station to record the absolute frame number for an edit and then store the edit location in a file that can be retrieved for later use.

The process described so far is called *assemble editing*. *Insert editing* is possible if a control signal is first laid down on the output tape. Then sequences can be inserted anywhere on the tape in forming the final sequence. This provides some nonlinear editing capability, but it is still not possible to easily lengthen or shorten a sequence without repositioning other sequences on the tape to compensate for the change.

Digital on-line nonlinear editing

To incorporate a more flexible nonlinear approach, fully digital editing systems have become more accessible [17] [33] [48]. These can be systems dedicated to editing, or they can be software systems that run on standard computers. Analog tape may still be used as the source material and for the final product, but everything between is digitally represented and controlled[9] (see Figure 1.9).

[9]It is interesting to note that the whole process from recording to projection can now be done digitally.

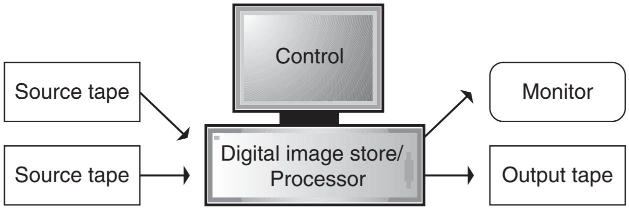

FIGURE 1.9

On-line nonlinear editing system.

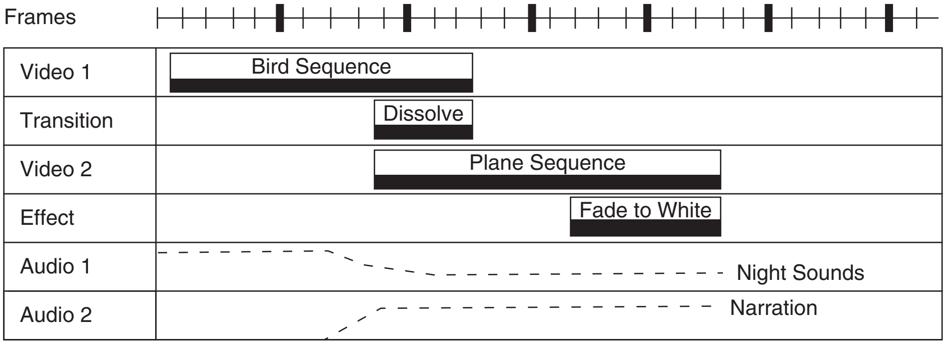

FIGURE 1.10

Simplified example of a time line used for nonlinear digital editing.

After a sequence has been digitized, an icon representing it can be dragged onto a time line provided by the editing system. Sequences can be placed relative to one another; they can be repeated, cut short, overlapped with other sequences, combined with transition effects, and mixed with other effects. A simplified example of such a time line is shown in Figure 1.10.

The positioning of the elements in the time line is conceptual only; typically the data in the digital image store is not actually copied or moved. The output sequence can be played back in real time if the disk random access and graphics display are fast enough to fetch and compile the separate tracks on the fly. In the case of overlapping sequences with transitions, the digital store must support the access of multiple tracks simultaneously so a transition can be constructed on the fly or the transition sequence needs to be precomputed (sometimes referred to as *rendering*) and explicitly stored for access during playback. When the sequence is finalized it can be assembled and stored digitally or recorded on video. Whatever the case, the flexibility of this approach, with the ability to change edits and try alternatives without generational degradation, makes nonlinear digital editing systems very powerful.

1.4.3 Digital video

As the cost of computer memory decreases and processor speeds increase, the capture, compression, storage, and playback of digital video have become more prevalent [42] [46]. This has several important ramifications. First, desktop animation has become inexpensive enough to be within the reach of the consumer. Second, in the film industry it has meant that compositing is no longer optical. Optically compositing each element in a film meant another pass of the negative through an optical film printer, which meant additional degradation of image quality. With the advent of digital compositing (see Appendix A.2), the limit on the number of composited elements is removed. Third, once films are routinely stored digitally, digital techniques can be used for wire removal and to apply special effects. These digital techniques have become the bread and butter of computer graphics in the film industry.

When one works with digital video, there are several issues that need to be addressed to determine the cost, speed, storage requirements, and overall quality of the resulting system. Compression techniques can be used to conserve space or reduce transmission time, but some compression compromises the quality of the image and the speed of compression/decompression may restrict a particular technique's suitability for a given application. During video capture, any image compression must operate in real time. Formats used for storage and playback can be encoded off-line, but the decoding must support real-time playback. Video resolution, video frame rates, and full-color imagery require that 27 MB/sec be supported for video playback.[10] An hour of uncompressed video requires just under 100 GB of storage.[11] While lossless compression (the original data can be exactly reconstructed) is possible, most video compression is lossy (not all of the original signal is recoverable) because of the favorable quality/space trade-off. There are several digital video formats used by different manufacturers of video equipment for various applications as well as video formats for streaming video and storage; these formats include D1, D2, D3, D5, miniDV, DVC, Digital8, MPEG-4, digital Betacam, H.261, and H.263. Better signal quality can be attained with the use of component instead of composite signals. Discussion of these and other issues related to digital video is beyond the scope of this book. Information on some of the more popular formats can be found in Appendix B.10.

1.4.4 Digital audio

Audio is just as important to computer animation as it is to traditional animation. Over the years, audio technology, like image technology, has gone digital. Early audio recordings used an electromechanical stylus to etch representations of the signal into wax drums or plastic platters. Later, the signal was used to modulate the magnetization of some type of ferromagnetic material on plastic tape. Digital audio has since taken over. Digital audio has the same advantages as digital imagery when it comes to duplicating and editing. Digital audio can be copied, cut and pasted, transitioned, and looped over without any degradation in signal quality—a distinct advantage over its analog counterpart. The sound capability in personal computers has dramatically improved over the years so that now high-quality sound capability is standard. As with digital imagery, there are file formats and compression standards to consider when dealing with digital audio. In addition, there is a standard for digitally controlling musical devices.

Digital musical device control

Musical instrument digital interface (MIDI) is a standard developed in 1983 to control musical instruments without being tied to any one instrument in particular. MIDI commands are keynote commands to musical devices and are intended to represent a musical performance. Mostly, the commands take the

[10] 640 pixels/scanline $\times$ 480 scanlines/frame $\times$ 3 bytes/pixel $\times$ 30 fps $=$ 27,630,000 bytes/sec.
[11] 27,630,000 bytes/sec $\times$ 3600 sec/hour $=$ 99,468,000,000 bytes/hour.

form of "note x on" and "note x off" where x is any of the standard musical notes. There are also control commands to set pitch, loudness, etc. Some devices can also send out MIDI commands as they are played in order to record the performance as keys are depressed and released. MIDI supports up to 16 channels and devices can be daisy-chained so that, for example, a device can be set up to respond only to a particular track.

Digital audio sampling

Sounds are pressure waves of air. In audio recording, the pressure waves are converted to some representation of the waveform. When it is recorded digitally, the wave is sampled at certain intervals—the sampling rate—with a certain number of bits per sample—the sample size—using a certain number of tracks. The sampling rate determines the highest frequency, called the Nyquist frequency, which can accurately be reconstructed. A voice signal can be sampled at a much lower rate than CD-quality music because the highest frequency of a voice signal is much lower than the highest frequency that might occur in a piece of music. The number of bits per sample determines how much distortion there is in the recorded signal. The number of tracks is how many independent signals comprise the music—one for mono, two for stereo, more for various "surround sound" recordings or for later editing. A voice signal and AM radio are sampled at approximately 10 K samples per second with 8-bits per sample using one track. CD-quality music is sampled at 44.1 K samples per second with 16-bits per sample using two tracks.

Similar to digital imagery, the digital recording can then be compressed for more efficient storage and transmission. The compression can either be lossless (the original signal can be reconstructed exactly) or lossy (some of the original signal is lost in the compression/decompression procedure—usually the very high frequencies). General data compression techniques can be used, but don't do as well on audio data as the compression schemes that use the fact that the file contains audio, referred to as being *perceptually based*. Compression of speech can use techniques that are less sensitive to preserving all of the frequency components of the sound. Common audio data compression techniques include MP3, MPEG-4 ALS, TTA, and FLAC.

1.5 A brief history of computer animation

1.5.1 Early activity (pre-1980)

The earliest computer animation of the late 1960s and early 1970s was produced by a mix of researchers in university labs and individual visionary artists [24] [25] [37]. At the time, raster displays driven by frame buffers were just being developed and digital output to television was still in the experimental stage. The displays in use were primarily storage tubes and refresh vector displays. Storage tubes retain an image indefinitely because of internal circuitry that continuously streams electrons to the display. However, because the image cannot be easily modified, storage tubes were used mainly to draw complex static models. Vector (calligraphic) displays use a display list of line- and arc-drawing instructions that an internal processor uses to repeatedly draw an image that would otherwise quickly fade on the screen. Vector displays can draw moving images by carefully changing the display list between refreshes. These displays were popular for interactive design tasks.

During this time period, static images were often recorded onto film by placing a camera in front of the display and recording an image of vectors on the screen. In this way, shaded images could be produced by opening the shutter of the film camera and essentially scan converting the elements (e.g., polygons) by drawing closely spaced horizontal vectors to fill the figure; after scan conversion was completed, the shutter was closed to terminate the image recording. The intensity of the image could be regulated by using the intensity control of the vector display or by controlling other aspects of the image recording such as by varying the density of the vectors. An image of a single color was generated by placing a colored filter in front of the camera lens. A full-color image could be produced by breaking the image into its red, green, and blue components and triple exposing the film with each exposure using the corresponding colored filter. This same approach could be used to produce animation as long as the motion camera was capable of single-frame recording. Single-frame recording required precise frame registration, usually available only in expensive film equipment. Animated sequences could be colored by triple exposing the entire film. The programmer (animator) was fortunate if both the camera and the filters could be controlled by computer.

The earliest research in computer graphics and animation occurred at the Massachusetts Institute of Technology in 1963 when Ivan Sutherland developed an interactive constraint satisfaction system on a vector refresh display [41]. The user could construct an assembly of lines by specifying constraints between the various graphical elements. If one of the graphical elements moved, the system calculated the reaction of other elements to this manipulation based on satisfying the specified constraints. By interactively manipulating one of the graphical elements, the user could produce complex motion in the rest of the assembly. Later, at the University of Utah, Sutherland helped David Evans establish the first significant research program in computer graphics and animation.

As early as the early 1960s, computer animation was produced as artistic expression. The early artistic animators in this period included Ken Knowlton, Lillian Schwartz, S. Van Der Beek, John Whitney, Sr., and A. M. Noll. Typical artistic animations consisted of animated abstract line drawings displayed on vector refresh displays. Chuck Csuri, an artist at Ohio State University, produced pieces such as *Hummingbird* (1967) that were more representational.

In the early 1970s, computer animation in university research labs became more widespread. Computer graphics, as well as computer animation, received an important impetus through government funding at the University of Utah [14]. As a result, Utah produced several groundbreaking works in animation: an animated hand and face by Ed Catmull (Hand/Face, 1972), a walking and talking human figure by Barry Wessler (*Not Just Reality*, 1973), and a talking face by Fred Parke (*Talking Face*, 1974). Although the imagery was extremely primitive by today's standards, the presentations of lip-synced facial animation and linked-appendage figure animation were impressive demonstrations well ahead of their time.

In 1972, Chuck Csuri founded the Computer Graphics Research Group (CGRG) at Ohio State with the focus of bringing computer technology to bear on creating animation [10]. Tom DeFanti produced the Graphics Symbiosis System (GRASS) in the early 1970s that scripted interactive control of animated objects on a vector display device. Later in the 1970s, CGRG produced animations using a real-time video playback system developed at North Carolina State University under the direction of John Staudhammer. Software developed at CGRG compressed frames of animation and stored them to disk. During playback, the compressed digital frames were retrieved from the disk and piped to the special-purpose hardware, which took the digital information, decompressed it on the fly, and converted it into a video signal for display on a standard television. The animation was driven by the ANIMA II language [15]. In the mid-1980s, Julian Gomez developed TWIXT [43], a track-based key-frame animation system.

In 1973, the first computer-language-based key-frame animation system, ANTICS, was developed by Alan Kitching at the Atlas Computer Laboratory under the auspices of the Royal College of Art in the United Kingdom. [19] [20]. ANTICS is a Fortran software package specifically designed for animators and graphic designers. It is a two-dimensional system that provides capabilities analogous to traditional cel animation.

In the mid-1970s, Norm Badler at the University of Pennsylvania conducted investigations into posing a human figure. He developed a constraint system to move the figure from one pose to another. He has continued this research and established the Center for Human Modeling and Simulation at the University of Pennsylvania. *Jack* is a software package developed at the center that supports the positioning and animation of anthropometrically valid human figures in a virtual world [7].

In the late 1970s, the New York Institute of Technology (NYIT) produced several computer animation systems, thanks to individuals such as Ed Catmull and Alvy Ray Smith [24]. At the end of the 1970s, NYIT embarked on an ambitious project to produce a wholly computer-generated feature film using three-dimensional computer animation, titled *The Works*. While the project was never completed, excerpts were shown at several SIGGRAPH conferences as progress was made. The excerpts demonstrated high-quality rendering, jointed figures, and interacting objects. The system used at NYIT was BBOP, a three-dimensional key-frame figure animation system [40].

In 1974, the first computer animation nominated for an Academy Award, *Hunger*, was produced by Rene Jodoin; it was directed and animated by Peter Foldes. This piece used a 2½ D system that depended heavily on object shape modification and line interpolation techniques [6]. The system was developed by Nestor Burtnyk and Marceli Wein at the National Research Council of Canada in conjunction with the National Film Board of Canada. *Hunger* was the first animated story using computer animation.

In the early 1980s Daniel Thalmann and Nadia Magnenat-Thalmann started work in computer animation at the University of Montreal [24]. Over the years, their labs have produced several impressive animations, including *Dream Flight* (N. Magnenat-Thalmann, D. Thalmann, P. Bergeron, 1982), *Tony de Peltrie* (P. Bergeron, 1985), and *Rendez-vous à Montréal* (N. Magnenat-Thalmann and D. Thalmann, 1987).

Others who advanced computer animation during this period were Ed Emshwiller at NYIT, who demonstrated moving texture maps in *Sunstone* (1979); Jim Blinn, who produced the *Voyager* flyby animations at the Jet Propulsion Laboratory (1979); Don Greenberg, who used architectural walk-throughs of the Cornell University campus (1971); and Nelson Max at the Education Development Center, who animated space-filling curves (1972).

Commercial efforts at computer animation first occurred in the late 1960s with Lee Harrison's SCANIMATE system based on analog computing technology [36]. Digital technology soon took over and the mid- to late-1970s saw the first serious hints of commercial three-dimensional digital computer animation. Tom DeFanti developed the GRASS at Ohio State University (1976), a derivative of which was used in the computer graphics sequences of the first *Star Wars* film (1977). In addition to *Star Wars*, films such as *Future World* (1976), *Alien* (1979), and *Looker*[12] (1981) began to incorporate simple computer animation as examples of advanced technology. This was an exciting time for those in the research labs wondering if computer animation would ever see the light of day. One of the earliest

[12]The film *Looker* is interesting as an early commentary on the potential use of digital actors in the entertainment industry.

companies to use three-dimensional computer animation was the Mathematical Application Group Inc. (MAGI), which used a ray-casting algorithm to provide scientific visualizations. MAGI also adapted its technique to produce early commercials for television.

1.5.2 The middle years (the 1980s)

The 1980s saw a more serious move by entrepreneurs into commercial animation. Computer hardware advanced significantly with the introduction of the VAX computer in the 1970s and the IBM PC at the beginning of the 1980s. Hardware z-buffers were produced by companies such as Raster Tech and Ikonas, Silicon Graphics was formed, and flight simulators based on digital technology were taking off because of efforts by the Evans and Sutherland Corporation. These hardware developments were making the promise of cost-effective computer animation to venture capitalists. At the same time, graphics software was getting more sophisticated: Turner Whitted introduced anti-aliased ray tracing (*The Compleat Angler*, 1980), Loren Carpenter produced a flyby of fractal terrain (*Vol Libre*, 1980), and Nelson Max produced several films about molecules as well as one of the first films animating waves (*Carla's Island*, 1981). Companies such as Alias, Wavefront, and TDI were starting to produce sophisticated software tools making advanced rendering and animation available off-the-shelf for the first time.

Animation houses specializing in three-dimensional computer animation started to appear. Television commercials, initially in the form of flying logos, provided a profitable area where companies could hone their skills. Demo reels appeared at SIGGRAPH produced by the first wave of computer graphics companies such as Information International Inc. (III, or triple-I), Digital Effects, MAGI, Robert Abel and Associates, and Real Time Design (ZGRASS).

The first four companies combined to produce the digital imagery in Disney's TRON (1982), which was a landmark movie for its (relatively) extensive use of a computer-generated environment in which graphical objects were animated. Previously, the predominant use of computer graphics in movies had been to show a monitor (or simulated projection) of something that was supposed to be a computer graphics display (*Futureworld*, 1976; *Star Wars*, 1977; *Alien*, 1979; *Looker*, 1981). Still, in *TRON*, the computer-generated imagery was not meant to simulate reality; the action takes place inside a computer, so a computer-generated look was consistent with the story line.

At the same time that computer graphics were starting to find their way into the movies it was becoming a more popular tool for generating television commercials. As a result, more computer graphics companies surfaced, including Digital Pictures, Image West, Cranston-Csuri Productions, Pacific Data Images, Lucasfilm, Marks and Marks, Digital Productions, and Omnibus Computer Graphics.

Most early use of synthetic imagery in movies was incorporated with the intent that it would appear as if computer generated. The other use of computer animation during this period was to "do animation." That is, the animations were meant not to fool the eye into thinking that what was being seen was real but rather to replace the look and feel of two-dimensional conventional animation with that of three-dimensional computer animation. Of special note are the award-winning animations produced by Lucasfilm and, later, by Pixar:

The Adventures of Andre and Wally B. (1984)—first computer animation demonstrating motion blur
Luxo Jr. (1986)—nominated for an Academy Award

Red's Dream (1987)
Tin Toy (1988)—first computer animation to win an Academy Award
Knick Knack (1989)
Geri's Game (1997)—Academy Award winner

These early animations paved the way for three-dimensional computer animation to be accepted as an art form. They were among the first fully computer-generated three-dimensional animations to be taken seriously as animations, irrespective of the technique involved. Another early piece of three-dimensional animation, which integrated computer graphics with conventional animation, was *Technological Threat* (1988, Kroyer Films). This was one of three films nominated for an Academy Award as an animated short in 1989; *Tin Toy* came out the victor.

One of the early uses of computer graphics in film was to model and animate spacecraft. Working in (virtual) outer space with spacecraft has the advantages of simple illumination models, a relatively bare environment, and relatively simple animation of rigid bodies. In addition, spacecraft are usually modeled by relatively simple geometry—as is the surrounding environment (planets)—when in flight. *The Last Starfighter* (1984, Digital Productions) used computer animation instead of building models for special effects; the computer used, the Cray X-MP, even appeared in the movie credits. The action takes place in space as well as on planets; computer graphics were used for the scenes in space, and physical models were used for the scenes on a planet. Approximately twenty minutes of computer graphics was used in the movie. While it is not hard to tell when the movie switches between graphical and physical models, this was the first time graphics were used as an extensive part of a live-action film in which the graphics were supposed to look realistic (i.e., *special effects*).

1.5.3 Animation comes of age (the mid-1980s and beyond)

As modeling, rendering, and animation became more sophisticated and the hardware became faster and inexpensive, quality computer graphics began to spread to the Internet, television commercials, computer games, and stand-alone game units. In film, computer graphics help to bring alien creatures to life. Synthetic alien creatures, while they should appear to be real, do not have to match specific audience expectations. *Young Sherlock Holmes* (1986, ILM) was the first to place a synthetic character in a live-action feature film. An articulated stained glass window comes to life and is made part of the live action. The light sources and movements of the camera in the live action had to be mimicked in the synthetic environment, and images from the live action were made to refract through the synthetic stained glass. In *The Abyss* (1989, ILM), computer graphics are used to create an alien creature that appears to be made from water. Other notable films in which synthetic alien creatures are used are *Terminator II* (1991, ILM), *Casper* (1995, ILM), *Species* (1995, Boss Film Studios), and *Men in Black* (1997, ILM).

A significant advance in the use of computer graphics for the movies came about because of the revolution in cheap digital technology, which allowed film sequences to be stored digitally. Once the film is stored digitally, it is in a form suitable for digital special effects processing, digital compositing, and the addition of synthetic elements. For example, computer graphics can be used to remove the mechanical supports of a prop or to introduce digital explosions or laser blasts. For the most part, this resides in the two-dimensional realm, thus it is not the focus of this book. However, with the advent of digital techniques for two-dimensional compositing, sequences are more routinely available in digital representations, making them amenable to a variety of digital postprocessing techniques. The first digital blue screen matte extraction was in *Willow* (1988, ILM). The first digital wire removal was in *Howard the Duck* (1986, ILM). In *True Lies* (1994, Digital Domain), digital techniques inserted atmospheric distortion to show engine heat. In *Forrest Gump* (1994, ILM), computer graphics inserted a ping-pong ball in a sequence showing an extremely fast action game, inserted a new character into old film footage, and enabled the illusion of a double amputee as played by a completely able actor. In *Babe* (1995, Rhythm & Hues), computer graphics were used to move the mouths of animals and fill in the background uncovered by the movement. In *Interview with a Vampire* (1994, Digital Domain), computer graphics were used to curl the hair of a woman during her transformation into a vampire. In this case, some of the effect was created using three-dimensional graphics, which were then integrated into the scene by two-dimensional techniques. More recently, The Matrix series (*The Matrix*, 1999; *The Matrix Reloaded*, 2003; *The Matrix Revolutions*, 2003, Groucho II Film Partnership) popularized the use of a digital visual effect used to show characters dodging bullets—slow motion was digitally enhanced to show unfilmable events such as a flying bullets.

A popular graphical technique for special effects is the use of particle systems. One of the earliest examples is in *Star Trek II: The Wrath of Khan* (1982, Lucasfilm), in which a wall of fire sweeps over the surface of a planet. Although by today's standards the wall of fire is not very convincing, it was an important step in the use of computer graphics in movies. Particle systems are also used in *Lawnmower Man* (1992, Angel Studios, Xaos), in which a character disintegrates into a swirl of small spheres. The modeling of a comet's tail in the opening sequence of the television series *Star Trek: Deep Space Nine* (1993, Paramount Television) is a more recent example of a particle system. In a much more ambitious and effective application, *Twister* (1996, ILM) uses particle systems to simulate a tornado.

More challenging is the use of computer graphics to create realistic models of creatures with which the audience is intimately familiar. *Jurassic Park* (1993, ILM) is the first example of a movie that completely integrates computer graphics characters (dinosaurs) of which the audience has fairly specific expectations. Of course, there is still some leeway here, because the audience does not have precise knowledge of how dinosaurs look. *Jumanji* (1995, ILM) takes on the ultimate task of modeling creatures for which the audience has precise expectations: various jungle animals. Most of the action is fast and blurry, so the audience does not have time to dwell on the synthetic creatures visually, but the result is very effective. To a lesser extent, *Batman Returns* (1995, PDI) does the same thing by providing "stunt doubles" of Batman in a few scenes. The scenes are quick and the stunt double is viewed from a distance, but it was the first example of a full computer graphics stunt double in a movie. More recently, the Spider Man movies (2002-present, Sony) make extensive use of synthetic stunt doubles. Use of synthetic stunt doubles in film is now commonplace.

Computer graphics show much potential for managing the complexity in crowd scenes. PDI used computer graphics to create large crowds in the Bud Bowl commercials of the mid 1980s. In feature films, some of the well-known crowd scenes occur in the wildebeest scene in *Lion King* (1994, Disney), the alien charge in *Starship Troopers* (1997, Tippet Studio), synthetic figures populating the deck of the ship in *Titanic* (1998, ILM), and various crowds in the Star Wars films (1977–2005, Lucasfilm) and The Lord of the Rings trilogy (2001–2003, New Line Cinema).

A holy grail of computer animation is to produce a synthetic human characters indistinguishable from a real person. Early examples of animations using "synthetic actors" are *Tony de Peltrie* (1985, P. Bergeron), *Rendez-vous à Montréal* (1988, D. Thalmann), *Sextone for President* (1989, Kleiser-Walziac Construction Company), and *Don't Touch Me* (1989, Kleiser-Walziac Construction

Company). However, it is obvious to viewers that these animations are computer generated. Recent advances in illumination models and texturing have produced human figures that are much more realistic and have been incorporated into otherwise live-action films.

Synthetic actors have progressed from being distantly viewed stunt doubles and passengers on a boat to assuming central roles in various movies: the dragon in *Dragonheart* (1996, Tippett Studio, ILM); the Jello-like main character in *Flubber* (1997, ILM); the aliens in *Mars Attacks* (1996, ILM); and the ghosts in *Casper* (1995, ILM). The first fully articulated humanoid synthetic actor integral to a movie was the character Jar-Jar Binks in *Star Wars: Episode I* (1999, ILM). More recently, Gollum in the *Lord of the Rings: The Return of the King* (2004, New Line Cinema[13]) and Dobby in the Harry Potter series (2001–2011, Warner Bros.) display actor-like visual qualities as well as the personality of a live actor not previously demonstrated in computer-generated characters.

However, a revolution is brewing in the realistic digital representation of human actors. At this point, we are not quite to the place where a digital human is indistinguishable from a live actor, but that time is drawing nearer. An early attempt at such realism was undertaken by *Final Fantasy: The Spirits Within* (2001, Chris Lee Productions), which incorporated full body and facial animation of human figures. The hair animation was particularly convincing; however, the facial animation was stiff and unexpressive. Several films effectively manipulated the appearance of facial features as a special effect including *The Curious Case of Benjamin Button* (2008, Paramount Pictures) and *Alice in Wonderland* (2010, Walt Disney Pictures). *Avatar* (2009, 20th Century Fox) with full body/face motion captures animated human-like creatures by mapping the performance of actors to the synthetic creatures. However, the most ambitious attempt at a synthetic actor is in the film *TRON: Legacy* (2010, Walt Disney Pictures), which animates a computer graphics version of a young Jeff Bridges. In this case, the audience (at least those of us old enough to remember what Jeff Bridges looked like when he was young) have a specific expectation of what a young Jeff Bridges should look like. The representation is effective for the most part; however, the film editing prevents the audience from closely inspecting the young Jeff Bridges and even so, there is an unreal eeriness about the figure. But this shows that synthetic actors are on their way to a theater near you. Advances in hair, clothes, and skin have paved the way, but facial animation has still not been totally conquered.

Of course, one use of computer animation is simply to "do animation"; computer graphics are used to produce animated pieces that are essentially three-dimensional cartoons that would otherwise be done by more traditional means. The animation does not attempt to fool the viewer into thinking anything is real; it is meant simply to entertain. The film *Hunger* falls into this category, as do the Lucasfilm/Pixar animations. *Toy Story* is the first full-length, fully computer-generated three-dimensional animated feature film. Other feature-length three-dimensional cartoons soon emerged, such as *Antz* (1998, PDI), *A Bug's Life* (1998, Pixar), *Toy Story 2* (1999, Pixar), *Shrek* (2001, PDI), and *Shrek 2* (2004, PDI). In 2002, *Shrek* won the first-ever Academy Award for Best Animated Feature.

Many animations of this type have been made for television. In an episode of *The Simpsons* (1995, PDI), Homer steps into a synthetic world and turns into a three-dimensional computer-generated character. There have been popular television commercials involving computer animation—too many to mention at this point. Many Saturday morning cartoons are now produced using three-dimensional

[13]For brevity, only the first production company itemized on the Internet Movie Database Web site (www.imdb.com) **is given when more than one production company is listed.**

computer animation. Because many images are generated to produce an animation, the rendering used in computer-animated weekly cartoons tends to be computationally efficient.

An example of rendering at the other extreme is *Bunny* (1999, Blue Sky Productions), which received an Academy Award for animated short. *Bunny* uses high-quality rendering in its imagery, including ray tracing and radiosity, as does *Ice Age* (2002, Blue Sky Productions). *The Incredibles* (2004, Disney/Pixar), which garnered another Academy Award for Pixar, included hair animation, subsurface scattering for illuminating skin, cloth animation, and skin-deforming muscle models. *Polar Express* (2004, Warner Bros.) advanced the use of motion capture technology to capture full body and face motion in animating this children's story.

Computer animation is now well-established as a (some would say "the") principal medium for doing animation. Indeed, at one time, both *Jurassic Park* and *Shrek 2* were on the top ten list of all time worldwide box office grossing movies [4].

Three-dimensional computer graphics are also playing an increasing role in the production of conventional hand-drawn animation. Computer animation has been used to model three-dimensional elements in hand-drawn environments. The previously mentioned *Technological Threat* (1988) is an early animation that combined computer-animated characters with hand-drawn characters to produce an entertaining commentary on the use of technology. Three-dimensional environments were constructed for conventionally animated figures in *Beauty and the Beast* (1991, Disney) and *Tarzan* (1999, Disney); three-dimensional synthetic objects, such as the chariots, were animated in conventionally drawn environments in *Prince of Egypt* (1998, DreamWorks). Because photorealism is not the objective, the rendering in such animation is done to blend with the relatively simple rendering of hand-drawn animation.

Lastly, morphing, even though it is a two-dimensional animation technique, should be mentioned because of its use in some films and its high impact in television commercials. This is essentially a two-dimensional procedure that warps control points (or feature lines) of one image into the control points (feature lines) of another image while the images themselves are blended. In *Star Trek IV: The Voyage Home* (1986, ILM), one of the first commercial morphs occurred in the back-in-time dream sequence. In *Willow* (1988, ILM), a series of morphs changes one animal into another. This technique is also used very effectively in *Terminator II* (1991, ILM). In the early 1990s, PDI promoted the use of morphing in various productions. Michael Jackson's music video *Black and White*, in which people's faces morph into other faces, did much to popularize the technique. In a Plymouth Voyager commercial (1991, PDI) the previous year's car bodies and interiors morph into the new models, and in an Exxon commercial (1992, PDI) a car changes into a tiger. Morphing remains a useful and popular technique.

1.6 Summary

Computer graphics and computer animation have created a revolution in visual effects and animation production. Advances are still being made, and new digital techniques are finding a receptive audience. Yet there is more potential to be realized as players in the entertainment industry demand their own special look and each company tries to establish a competitive edge in the imagery it produces.

Computer animation has come a long way since the days of Ivan Sutherland and the University of Utah. Viewed in the context of the historical development of animation, the use of digital technology is indeed both a big and an important step. With the advent of low-cost computing and desktop video, animation is now within reach of more people than ever. It remains to be seen how the limits of the technology will be pushed as new and interesting ways to create moving images are explored. Of particular importance is the evolution of human figure modeling, rendering, and animation. This technology is on the verge of making a significant impact on both special effects and animated films as synthetic figures become more indistinguishable from real people. In addition to human figure animation, more sophisticated mathematical formulations for modeling cloth, water, clouds, and fire are generating more complex and interesting animations. As these and other advanced techniques are refined in the research labs, they filter down into off-the-shelf software. This software is then available to the highly talented digital artists who create the dazzling visuals that continually astound and amaze us in movie theaters and on the internet.

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