# THE ART AND PRACTICE OF 3D COMPUTER-GENERATED CHARACTER ANIMATION

**Maria Enderton**

**Computer Science Capstone Paper**

**Macalester College**

**4/30/2003**

**Advisor: Yvonne Ng, College of St. Catherine**

# TABLE OF CONTENTS

## LIST OF FIGURES

# ABSTRACT

The use of highly realistic computer-generated 3D virtual worlds, though technically and visually impressive, does not in and of itself guarantee a successful computer-generated character animation. This capstone explores the art and practice of computer animation, particularly character animation. This exploration includes discussions of the following topics: First, this capstone delves into the definitions of animation and its various forms, including character animation. It then provides some highlights from the histories of both traditional and computer animation. It continues with an overview of general approaches to computer animation, with a focus on the motion generation techniques of 3D animation. Next, it investigates the relationship between the quest for "realism" in computer animation and the quest for successful computer-generated character animation. Finally, this capstone concludes with an examination of the use of the fundamental principles of traditional animation in the creation of successful computer-generated character animation. In the conclusion, the capstone also includes a deliberation on whether or not modern computer animation techniques one day can and will, and should, replace the traditional animation process.

## The Art and Practice of Computer-Generated Character Animation

## 1. INTRODUCTION

### 1.1 What is Animation?

In 1906, J. Stuart Blackton produced what many consider the first animated film, Humorous Phases of Funny Faces, a three-minute film created using chalk and a blackboard (figure 1). In 2001, Disney/Pixar released Monsters, Inc., a full-length feature created using three-dimensional (3D) computer animation (figure 2). The computer-

**Figure 1:** Humorous Phases of Funny Faces (1906), J. Stuart Blackton

**Figure 2:** Monsters, Inc. (2001), Disney/Pixar

generated fur of James P. Sullivan, the large blue monster in Monsters, Inc., consisted of 3.2 million independently modeled hairs (Weiss, 2002). These animations seem worlds apart in complexity and in techniques used; yet, they are both animations. Why is that so? That is, in what ways are they linked? Both of these animations attempt to tell stories through the formation and animation of characters. But, what makes them animations? The definitions of animation and its various forms require further examination.

*Animation* has been defined in a number of ways. In her book Art in Motion: Animation Aesthetics, Maureen Furniss stated that "arriving at a precise definition is extremely difficult, if not impossible" (1998, p.5). The term *traditional animation,* or *conventional animation*, has often been identified as the process of photographing a series of individually hand-drawn images on successive frames of film. Computer animation, however, does not fit within this definition.

In order to find a definition that also encompasses computer animation, animation should be considered from a technique-independent perspective. As the root *animate* suggests, animation concerns motion. Truly, "The art of animated film is in the action… Animation is not making drawings move. It is, in essence, drawing movement" (Taylor, 1996, p.7). More practically, one can characterize animation as, "The production of consecutive images, which, when displayed, convey a feeling of motion" (Hodgins, O'Brien, and Bodenheimer, 1999, p.686). The display of consecutive images taken directly from reality, or photographs, constitutes a conventional live-action film. Therefore, in animation, these consecutive images must also be ones not taken directly from reality. This definition of animation which emphasizes the illusion or sense of motion more accurately covers the range of animated works, including computer-generated animation.

Though traditional hand-drawn animation and, more recently, computer animation, have been the most prevalent varieties of animation, other equally valid forms exist. Various forms of animation have been used in combination with other types of animation, as well as in combination with live-action film footage. Traditional animators have used an assortment of drawing instruments in the creation of this 2D mode of animation. These instruments have included a variety of paints, pencils, inks, charcoal, and markers. Other media for non-computer-generated 2D animation have included cut-outs and sand (figures 3 and 4, Taylor, 1996).

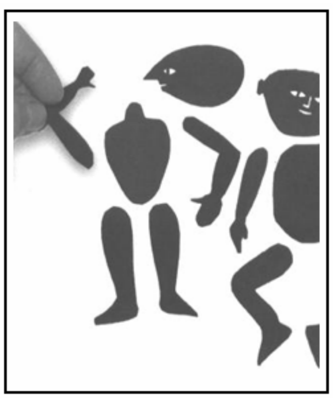


**Figure 3:** Cut-outs as a medium for in animation, Taylor (1996, p.59)
**Figure 4:** Sand as a medium for animation, Taylor (1996, p.69)

Though commonly associated primarily with computers, 3D animations are not limited to computers. Animators have explored the third dimension through *stop-action animation*. In this form of animation, the animator uses physical models, such as puppets and clay figures, which are positioned or manipulated and then photographed for each frame. The Academy Award-winning Wallace and Gromit series, done using modeling clay, is among the most famous recent examples of such animations. Though clay and puppets are the most common media for stop-action animation, in reality, "You can animate anything – with pipe cleaners, pennies, pop-tops, pajamas, plates, penknives, pansies, peas, pills, and pins. As long as you can lift it and move it, it's possible to animate it" (Laybourne, 1988, p. 50). Three-dimensional computer animation holds certain important similarities to stop-action techniques. In both, animators first model 3D figures that they then position and manipulate. The term computer animation most often refers to 3D computer animation. However, both 2D and 3D computer animation techniques exist.

The range of animation techniques demonstrates that the medium used is not the crucial element of animation. Rather, the crucial element is the manner in which the animator manipulates this media in order to create an illusion of motion, and, in a sense, the illusion of life. Animation is an art, whether or not a computer is involved in the production. "Some people work out their designs with pencil and paper, some prefer pixels. All these methods can inspire new and innovative designs" (Maestri, 1996, p.4). Conversely, poorly designed animations may result from any of the animation techniques, including computer animation. In fact, as the technology becomes more advanced and computer animations become easier to generate, poorly designed computer animations also become easier to generate.

## 1.2 Animation for Entertainment and Character Animation

This capstone paper will concentrate primarily on animations produced for entertainment purposes, particularly character animation. These animations produced for entertainment may appear in various forms, including feature films, television programs and commercials, games, and special effects.

A further classification of entertainment animation is *character animation*. The primary goal of character animation is the telling of a story through the use of characters, characters that are ideally compelling and engaging to the audience. Characters have distinctive personalities, and the best characters reveal their emotions and thought processes through their actions. These necessary aspects of characters apply regardless of media used. Walt Disney said, "In most instances, the driving force behind the action is the mood, the personality, the attitude of the character – or all three. Therefore the mind is the pilot."

Most authors of computer-generated character animation utilize 3D techniques. Computer animation has also been used with great success with regard to a number of more practical applications. Computer animation has been used in educational, training, medical, and computer-aided design (CAD) animations, as wells as in simulations of various sorts, including flight simulations. At times these computer animations entail the creation of interactive virtual environments, or *virtual realities.* Though important applications, the scope of this paper does not include these uses of computer animation technologies and techniques. This paper will concentrate primarily on the character animation created to be viewed in one particular way, in that the story does not change between viewings, as is the case with movies.

## 1.3 Goals and Outline

Within the realm of animation for entertainment purposes and character animation, this capstone paper seeks to place the current state of computer animation, particularly 3D computer animation, within the context of animation as a whole. Computer animators may be tempted to include extra features and elements to their animations simply because the computer technologies and techniques allow them to do so. Though these additions may be visually or algorithmically impressive, they could easily add unnecessary computational complexity while subtracting from the overall objectives of character animation.

Computer animation, and 3D computer-generated character animation, did not develop in a vacuum; its practice, and art, can benefit from an examination of the history of techniques and principles of traditional animation. Traditional animators have told stories through the illusion of motion since the beginning of the last century, an era in which computers did not exist. During this time these animators have developed and refined principles of successful character animation. It is appropriate and beneficial for today's computer animators to take advantage of and draw lessons from their predecessors' hard work.

Section 2 provides some historical highlights both of traditional animation and of computer-generated animation. Section 3 offers an overview of the general approaches to animation using computers, and includes both 2D and 3D computer animation approaches. Section 4 extends section 3 through a discussion of the motion generation techniques of 3D computer animation.

Within academic computer animation researchers, many animators have placed a large focus on the manufacture of highly realistic animation, or animation indistinguishable from the "real thing." This focus has, on occasion, extended to animations for entertainment purposes and character animations. This realism in animations can be considered in two respects. First, an animation may be realistic vis-à-vis the extent to which each image or frame is completely photo-realistic. Second, an animation can be realistic with respect to the nature of the movement of the objects or characters. Thus, an animated human or animal that is not photo-realistic can still move (e.g. walk, run, or dance) in a realistic fashion, in that it moves as the actual human or animal would move. Section 5 discusses what this drive for realism entails and its relationship to computer-generated character animation.

Prior to the advent of the use of computers in animation, animators developed and refined some fundamental principles of traditional animation, which were applied in order to create successful character animation. *Successful character animation* refers to animations that appeal the audiences by telling engaging stories using characters. Furthermore, the characters are ones to whom the audience can relate or connect; they are characters full of emotions, thoughts, and individualistic personalities. Section 6 discusses these fundamental principles. It also describes the manner in which these principles might apply with regard to various computer animation techniques. Essentially, this section asks whether or not do the fundamental principles of traditional animation apply to computer animation; and if so, how they apply. Section 7 supplies a conclusion, which includes a discussion of the debate regarding whether computer animation techniques might one day completely replace the traditional hand-drawn animation process.

## 2. ANIMATION HISTORY HIGHLIGHTS

### 2.1. Traditional Animation

Animation in film form first made its appearance at the dawn of the twentieth century with J. Stuart Blackton's Humorous Phases of Funny Faces (1906; figure 1). A decade later Winsor McCay produced the first popular, widely-seen animations, in particular 1914's Gertie the Dinosaur. In this same year, the patent of animated film's first major technical development, cels, was filed. *Cels* are pieces of translucent celluloid on which animators draw; they allow animators to composite several layers of drawings into the final product, thus permitting the reuse of time-expensive background drawings. Though today these translucent sheets are made with acetate, the term cel has persisted (Laybourne, 1998). Traditional animation is sometimes referred to as *cel animation*, because cel animation became the most common technique of traditional animation.

Another popular and influential animation technique developed and refined in the first half of the century was *stop-action animation*, which involves the use of physical models, such as puppets and clay figures, which the animator positions or manipulates and then photographs for each frame of the animation. An early pioneer of this process, Willis O'Brien began using the technique in 1917 with the short film, The Dinosaur and the Missing Link, and increased the technique's profile with the highly successful King Kong in 1933 (Parent, 2002). Stop-action animation techniques are still in use today. Recent examples include Nick Park's Wallace and Gromit series and the Tim Burton productions The Nightmare Before Christmas (1993) and James and the Giant Peach (1996).

In 1926 Lotte Reiniger produced the first feature-length animated film, The Adventures of Prince Achmed (Vince, 2000). In the mid-1920s Otto Messmer created Felix the Cat, which was the first animated character with a popularly identifiable


**Figure 5:** Felix the Cat, Otto Messmer

personality; it was the first animated character that the general public could easily identify (figure 5). It was also the most commercially successful cartoon of that time period (Parent, 2002).

The late 1920s saw the beginnings of the Walt Disney studio's reign on the world the conventional animation. The animators at Disney studio were instrumental in a number of major technical developments and refinements, including cel animation, the multiplane camera, the use of sound, and the use of color. Steamboat Willie (1928), starring Mickey Mouse, was the first animated film to use synchronized sound; furthermore, Mickey went on to become on of the most identifiable animated personalities ever.

The Disney studio was the source of the first major advancement of animation as an art form. Walt Disney and his animators stressed the importance of the character's personality and appeal; "He promoted the idea that the mind of the character was the driving force of the action" (Parent, 2002, p.9). In the late 20s and through the 30s, the animators at Disney developed and honed a set of practices that acted as the "rules of the trade," soon to become the fundamental principles of traditional animation. Frank

Thomas and Ollie Johnston, animators at Disney during this period in the 1920s and 1930s, define and illustrate these principles in <u>The Illusion of Life: Disney Animation</u>, originally published in 1981.

Traditional animators began telling stories through motion long before the advent of the computer and continue to do so despite today's advanced computer animation technology. Thus, it is appropriate and beneficial for today's computer animators to consider and take advantage of these fundamental principles of successful character animation. These principles include anticipation, appeal, arcs, exaggeration, follow through and overlapping action, secondary action, slow in and slow out, squash and stretch, staging, and timing. In section 6, these principles will be defined and considered more in-depth.

### 2.2. Computer Animation

The use of computers in the creation of animation in film can fulfill one of several roles or functions. The number of these functions has increased over time as technology has become cheaper and easier to use, and as animators and computer scientists have expanded the boundaries of what constitutes animation.

The most basic computer-based animation tools act as assistants to the traditional hand-drawn animation process, e.g. CAPS (Computer Animation Production System) developed by Pixar for Disney. When using CAPS, animators scan all of their drawings into digital images ("Bringing Drawings Life", n.d.). The animators then use CAPS to color these digitized images, check them for inconsistencies, and eventually composite the layers to form the final animation, which is then transferred to film. In fact, through the use of this system, Disney has replaced the use of physical cels with "digital cels." First used in 1989, Disney has used CAPS for every traditional animation since <u>Beauty and the Beast</u> in 1992. Though the physical cel disappeared, and though the animators rely heavily on computers, the final animation is produced in a manner similar to traditional animation, with its individually created and composited layers. It is "not animation by computer but animation using computers" ("Bringing Drawings Life", n.d., ¶ 17). Animo, developed by Cambridge Animation Systems, is similar computer system widely used for coloring drawings that have been scanned into digital form (Taylor, 1996).

Though the initial development of interactive computer systems and computer animation and imaging technology occurred in the 1950s and 1960s, before the advent of microcomputers in the mid-1970s, virtually none of the computer animations produced were done so with artistic or entertainment-related intentions. The early computers and corresponding graphics technology were fairly expensive, limited by hardware, and quite difficult to operate, requiring significant programming expertise. Almost all early computer graphics applications were of a practical nature; they were generally associated with the military, manufacturing, or the applied sciences. "Many of these early creators had to put more effort into the process of creating the works than into the form and contents of the works themselves (Kerlow, 1996, p. 8).

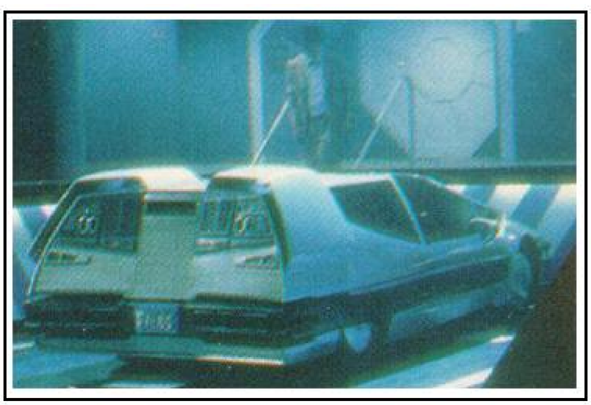
Most of this early computer graphics development occurred at government-funded academic research laboratories. In the 1970s university research labs dedicated to computer animation and imaging grew in number and the technology of computer animation further developed, particularly in three-dimensional representations. In 1974

Rene Jodion and Peter Foldes produced and animated Hunger/La Faim using a computer animation system that relied on object shape modification and line interpolation techniques (figure 6). It was among the earliest computer-generated animations to be

**Figure 6:** Hunger/La Faim (1974), Rene Jodion & Peter Foldes

considered successful as an artistic venture as well as a technical one. It was also the first computer animation to be nominated for an Academy Award (Parent, 2002).

As computer technology and techniques continued to develop, commercial animations began to proliferate in the 1980s as. At this time a number of commercial animation production houses formed, houses specializing in 3D computer animation; much of this animation was created for entertainment purposes, including for films and television commercials. The 1982 Disney Production's feature film TRON was significant for its relatively substantial use of computer animation within a full-length film; it had over 20 minutes of computer animation. TRON was also one of the first films to composite computer animations with live action footage. In this case, the imagery and animations were not intended to simulate reality. In 1985, The Last Starfighter, for the first time in film, incorporated a substantial amount of computer animation intended to look highly realistic. Figure 7 shows a physical model of a car



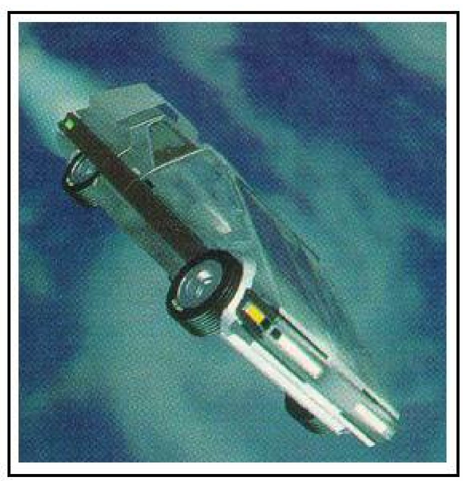


**Figure 7:** Physical car model, The Last Starfighter (1985), Digital Productions
**Figure 8:** Computer-generated car model, The Last Starfighter (1985), Digital Productions

used in some scenes, while figure 8 shows the computer-generated model used in other scenes. The 1990s brought the arrival of the first full-length entirely computer animated films, beginning with Disney/Pixar's Toy Story in 1995, and followed in 1998 by both PDI/Dreamworks' Antz and Disney/Pixar's A Bug's Life.

## 3. GENERAL APPROACHES TO COMPUTER ANIMATION

The various computer animation techniques can be used alone to create an animation, or they can be used in combination with other animation techniques or live-action film techniques to generate hybrid productions. These computer animation techniques fall into two general categories, *two-dimensional (2D)* and *three-dimensional (3D)* techniques. The bulk of current research concerns 3D techniques. Furthermore, most computer-generated character animation makes use of 3D techniques (Hodgins, O'Brien, & Bodenheimer, Jr., 1999). Generally speaking, 2D techniques tend to concentrate on image manipulation, whereas 3D techniques typically create virtual 3D worlds filled with modeled objects that can then be animated. The general process of 3D animation contains three stages, modeling, animation or motion generation, and rendering. The remainder of this section will review computer techniques of these two major categories, beginning with 2D techniques. The discussion of 3D techniques will briefly cover modeling and rendering, but will concentrate primarily on the motion generation stage, and will cover techniques that are more-or-less extensions of traditional animation, as well as techniques that are more unique to computer animation.

### 3.1 Two-Dimensional Computer Animation

Two-dimensional animation techniques include sprite-based animation, the embedding of graphical objects into an existing image, the removal of graphical objects from an existing image, and image morphing, arguably the most visually striking technique (Hodgins, O'Brien, & Bodenheimer, Jr., 1999). A *sprite* is a graphical object, in this case, a bitmap image, which is then composited over a background. *Compositing* is the process of combining two or more separate images into a single, new image. With *sprite animation*, the most common 2D technique, the animator creates a sequence of positions of the sprite and this sequence is then composited one position per frame onto a background. Thus, the illusion of motion is created, in similar fashion to cel animation.

Strictly speaking, sprite animation involves only positional movement, and not changes in shape, size, color, or any other variables. Generally, however, the animators create a set of graphical objects or bitmap images to be composited, such as a set of different poses for an animal in motion or a set of different sizes of the image. Thus this form of animation has been termed *sprite-based animation*. Though it can be accomplished exceptionally quickly, sprite-based animation is limited because the sprites used come from a fixed library. Therefore, animators most often employ sprite-based animation in situations where rendering speed is more important than realism, e.g. interactive media, including games (Hodgins, O'Brien, & Bodenheimer, Jr., 1999).

The advent of cheap digital technology in the late 1980s allowed for digital film storage. Consequently, the use of certain computer animation techniques in film began to flourish. Having a film sequence stored digitally permits digital special effects processing, which includes embedding of and removal of graphical objects from video footage. Often the graphical objects are created through 3D animation techniques, and then these objects are added to the image by these 2D effects. An example is the addition of dinosaurs in scenes in Jurassic Park. Object removal such as the removal of prop supports often goes unnoticed, but can be equally dramatic. In Speed, the bus jumps a gap in the freeway, a gap created by the digital removal of a piece of the freeway (Hodgins, O'Brien, & Bodenheimer, Jr., 1999).

*Morphing*, short for *metamorphosis*, involves the animated transformation of an image or model of one object into an image or model of another object. In its 2D incarnation, commonly called *image morphing*, the morphing transpires between two digital images, the *source* and *destination images*. An animator can apply image morphing to digitally-stored conventional films or to renderings of 3D computer animated scenes. Terminator II (Industrial Light and Magic) and the Michael Jackson video "Black or White" (Pacific Data Images), both 1991, are two of the most memorable early major applications of this type of morphing. "Black or White" was notable for its use of morphing between people with had markedly different facial attributes. The fluid transitions are the result of a combination of color interpolation of each pixel, and warping.

A *warp* is a 2D geometric transformation; when applied to an image a warp distorts it. The process is as follows:

> As the morphing proceeds, the first image (source) is gradually distorted and is faded out, while the second image (target) starts out and is faded in. Thus, the early images in the sequence are much like the first image. The middle image of the sequence is the average of the first image distorted halfway towards the second one and the second image distorted halfway back towards the first one. The last images in the sequence are similar to the second one. Then, the whole process consists of warping two images so that they have the same "shape" and then cross dissolving the resulting images (Zhang, 2001, ¶ 1)

Figure 9 shows a sequence of frames from a morph in "Black or White." The difficulty

**Figure 9:** Image morphing in "Black or White" (1991), Pacific Data Images

in morphing lies in the computation of the warps for distortion; here, the animator must specify corresponding elements in the source and destination images, which are then used to control the evolution of the distortion. There are two primary approaches, which differ in they way the animator specifies the corresponding elements, or features: mesh-based methods and feature-based methods (Magnenat-Thalmann & Thalmann, 1997).

In the *mesh-based approach*, the elements are stipulated by a nonuniform mesh, which is generated from animator-specified coordinate grids over each image (Parent, 2002). In the *feature-based approach*, the elements are specified by animator-defined *feature lines*, a set of points or line segments on each image. Though automatic feature detection remains an active area of research, animators generally must specify individually the elements, making image morphing a labor intensive process (Hodgins, O'Brien, & Bodenheimer, Jr., 1999). 3D morphing involves the transformation of the actual models rather than the transformation of the images of these models; this technique will be considered in an upcoming section (see section 4.1).

## 3.2 Three-Dimensional Computer Animation

Three-dimensional computer animation production is generally presented as a series of stages: modeling, animation, and rendering. During the *modeling* process, an animator defines the shape, or form, and placement of 3D objects in 3D environments. During the *animation* or *motion generation* stage the animator specifies how these objects are to move within their environments, as well as specifying any changes of the properties of the lights, cameras, and surfaces/textures. During the *rendering* process, all the data that define the 3D objects and environments are translated into 2D images. This defining data include information about the models, cameras, lighting, and surface characteristics, or textures. During this rendering stage most of the visual characteristics of the objects and environments are determined.

Though modeling must be accomplished in order to begin motion generation, and though rendering is the final step in the production of a finished animation, in reality the processes are highly interrelated. Separating these stages is generally a matter of conceptual convenience, and they should not be considered completely independent stages. Generally speaking, the more complex and calculation heavy the models are, the more complex and time-consuming the animation and rendering processes are. "The animation will be influenced by the way the objects are modeled, and the modeling of the objects will be influenced by the demands of the animation" (O'Rourke, 1998, p.14). Additionally, the way in which the animator models an object affects the possible types of manipulations for that model. Because the choice of models is generally important in determining the relative ease of various motion generation techniques, some of the common modeling approaches will be discussed in the remainder of this section. Section 4 will discuss the major animation, or motion generation, techniques.

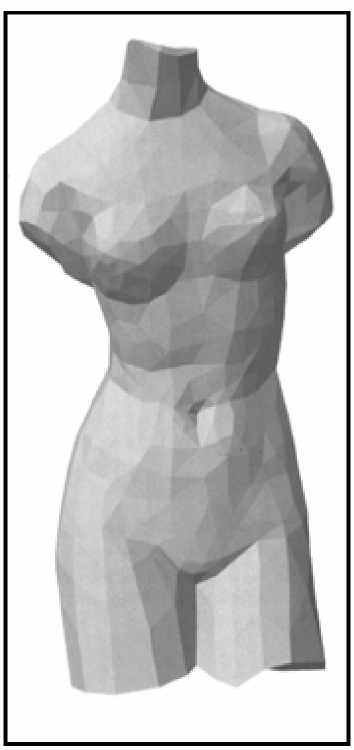
## 3.3 Three-Dimensional Computer Modeling Techniques

The creation of a computer model means defining an object or character in terms of its *shape*, or *form*, usually through the use of one of the following approaches: surface, solid, or particle system modeling. An animator or animation system may use *solid modeling*; here, the animator defines the object as a solid mass, which is then assigned additional properties of a solid, including density and weight. However, most often, the animator uses *surface modeling*, in which the object's shape is defined by the surfaces that enclose it, because this approach is less computationally intensive while still providing a sufficient model.  Another modeling approach is the use of a *particle system*, or collection of points, which animators often use for phenomena not easily modeled using the surfaces, such as fire, clouds, water flow and spray, mist, and smoke. Animation with particle systems will also be considered later, in the section on procedural motion generation techniques (section 4.2).  Since surface modeling is by far the more common approach, the techniques that follow are primarily surface-modeling ones (O'Rourke, 1998).

There are two predominant modes for creating surfaces in 3D computer modeling: Using polygons and using splines and patches.  In *polygonal modeling* the animator defines the surface using flat polygons.  In the real world, especially within nature, curved lines and surfaces are much more common than straight ones.  When modeling curved surfaces with polygons, polygonal approximation is used, where large numbers of very small polygons are used to approximate the curvature of the surface.

For a complex model with many surfaces that need to appear curved, the number of needed polygons can become very large.  If not enough polygons are used to approximate the curves, after shading is added, the model often possesses a faceted appearance (figure 10).  This is generally not the desired result, particularly with character modeling.

Though polygonal modeling can be used successfully with complex models (figure 11), the large number of needed polygons will often greatly affect the speed of processing the model.  Thus, this approach can be very inefficient.  Though there are



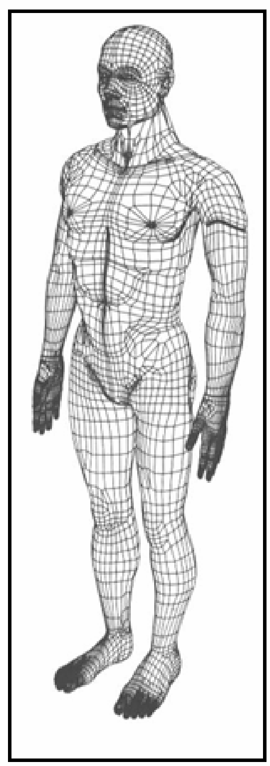


**Figure 10 (left):** A faceted model as the result of polygonal surface modeling, Ratner (1998, p.14)
**Figure 11(right):** A complex model using polygonal surface modeling, O'Rourke (1998, p.20)

certain methods to reduce the number of polygons while keeping approximately the original shape, often animators will choose to use curves or splines and patches. This second method of modeling surfaces uses curves as its building blocks. Linear approximation is one approach to representing curves; it uses a series of straight lines to approximate a curve, conceptually similar to polygonal approximation. It has similar drawbacks as well. Therefore, many modeling systems make use of splines, a geometric method for drawing curves, in which the placement of control points determine the shape of the curve.

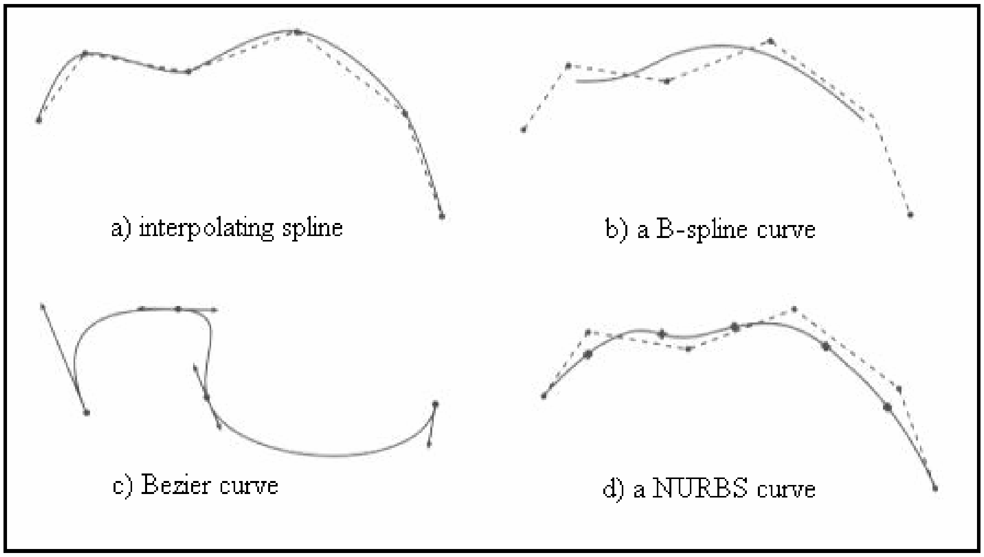



**Figure 12:** Example curves/splines, O'Rourke (1998, pp.23-25)

For interpolating splines, the spline curve passes through every control point; for approximating splines, the spline curve need not pass through every control point, but rather it passes near some of the control points. Figure 12 (a) shows an example of an interpolating spline. Figure 12 (b), (c), and (d) show examples of a B-spline curve, a Bezier curve, and a NURBS (Non-Uniform Rational B-Spline) curve, three popular types of splines in computer modeling. Moving a curve through space defines a curved surface; a patch is a curved surface generated using spline curves (figure 13, using NURBS curves).

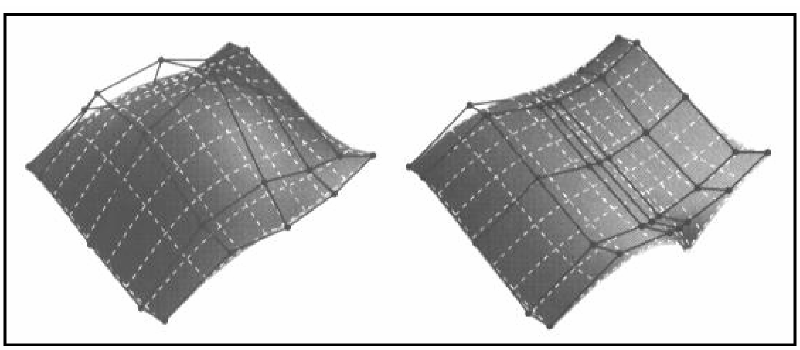


**Figure 13:** A patch, using NURBS curves, O'Rourke (1998, p.27)

Certain basic shapes, collectively known as *geometric primitives*, are so commonly used within modeling, that nearly all modeling systems handle them separately. Whether the underlying system created these primitives using polygonal modeling or using curved surfaces, most animation systems provide the user some subset of primitives, which may include cubes, spheres, cylinders, cones, toruses, and regular polyhedra. The combination of these primitives to form a more complex model conceptually parallels the physical creation of models in the traditional technique of stop-action animation.

The animator may also need to provide information about how the modeled object can move, particularly when that model is an interconnected collection of modeled parts, for example the various parts of a human model. "Three-dimensional objects can be grouped together in a limitless number of ways in order to create structures that define the ways in which these models are transformed, how they relate to / one another, how they are rendered, and how they behave when animated" (Kerlow, 1996, pp.63-64).

Often the most appropriate solution is to organize the model using a *hierarchical structure*, which results in a set of levels. An operation on the highest level affects the entire model as a unit. An operation on a lower level affects only the parts at that level and any further lower levels. With a believable human hierarchical model, an animator should be able to move an individual finger without moving the model's entire hand, but should not be able move the model's entire hand without also moving its fingers. Such hierarchies are commonly represented schematically. Figures 14 and 15 show schematic representations for the following two hierarchical models: A simple one, a car, and a more complex one, a human. Additionally, complex systems may require the use of hybrid models, which combine different types of models (Hodgins, O'Brien, & Bodenheimer, Jr., 1999).

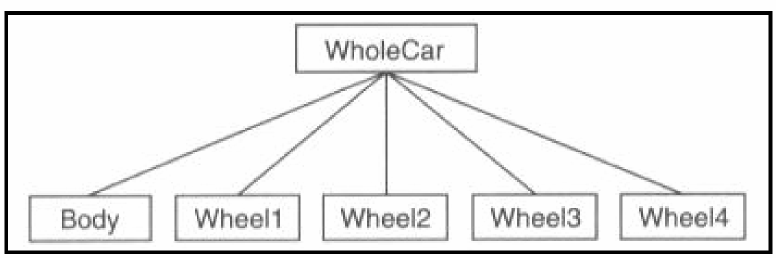



**Figure 14:** The schematic representation of a simple hierarchical model, a car, O'Rourke (1998, p.55)

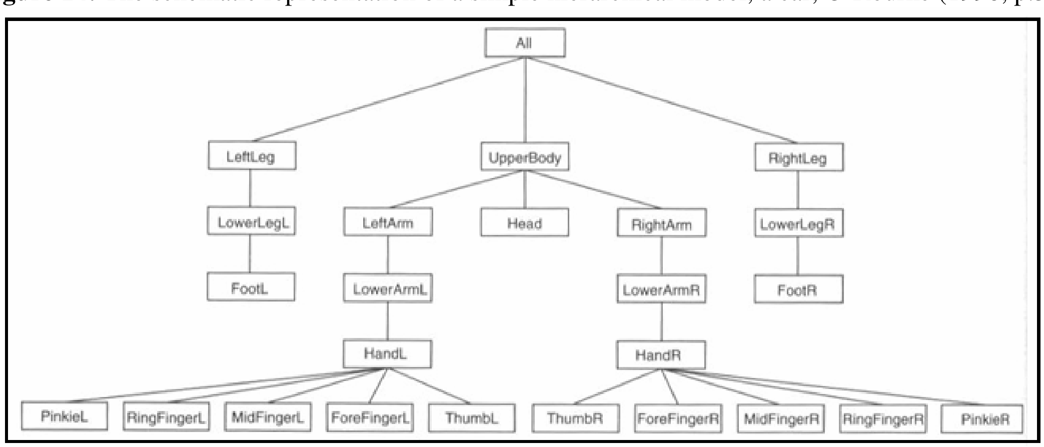



**Figure 15:** The schematic representation of a complex hierarchical model, a human, O'Rourke (1998, p.60)

# 4. THREE-DIMENSIONAL COMPUTER MOTION GENERATION TECHNIQUES

The simplest, most direct 3D *motion generation* technique is to manually arrange all the objects in a sequence; however, the use of this technique is typically monumentally time-consuming, particularly if one wants to produce believable motion for all but the most simple models. The 3D motion generation techniques most commonly used in character animation can be categorized into *model-based methods* and *motion capture-based methods*. Model-based techniques, the larger and more conceptually important of the two groups, can be further divided into *kinematic*, *procedural*, and *behavioral* approaches. These approaches, kinematic, procedural, behavioral, and motion capture-based, will each be considered in turn, followed by a discussion that compares and contrasts these approaches.

## 4.1 Kinematic Approaches

*Kinematic*, or *geometric*, techniques for motion generation are based on changing the positions and orientations of models in the 3D environments. These techniques typically rely heavily upon the animator, who provides the geometric information, which may include coordinates, angles, velocities and accelerations, and shape defining points. "Kinematic control refers to the movement of objects irrespective of the forces involved in producing the movement" (Parent, 2002, p. 174). This category makes heavy use of *keyframing*; at times, these terms are considered synonymous.

*Keyframe-based* systems are among the oldest computer animation systems, and remain among the most common for character animation. These systems borrow their name from the related traditional animation technique. In traditional animation, keyframing systems were developed in large part by Disney as a way to efficiently increase frame production. With keyframing, the master animator draws the most important frames, the *keyframes*. These keyframes are the frames containing poses or positions most necessary in order to produce the desired movement. The assistant animators would then draw the *in-betweens*, which are all the frames that fall between the keyframes (figure 16). In computer keyframing systems, the computer serves as the

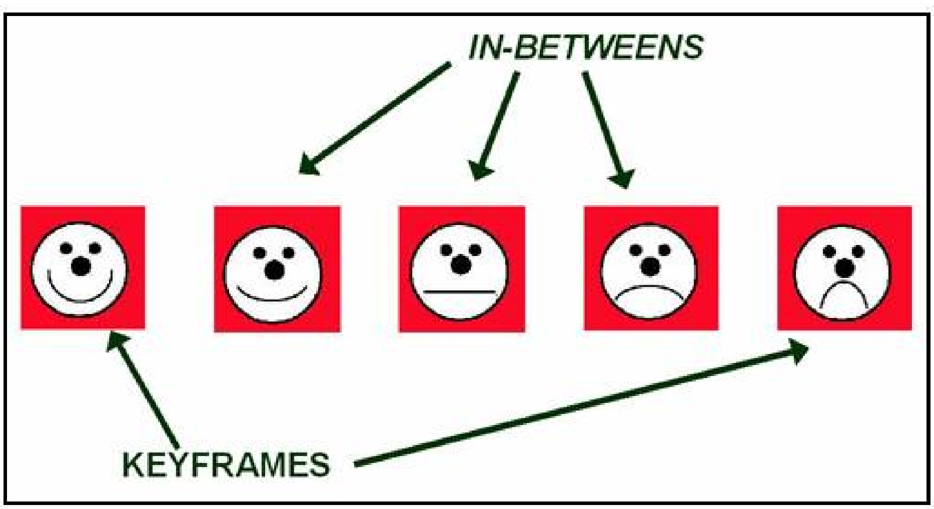



**Figure 16:** Keyframes and in-betweens

assistant animator, creating the in-betweens for the keyframes determined by the animator. The system creates these in-betweens by calculating the intermediate transformation values of the object's positional characteristics, e.g. translation, rotation, and scale, according to an interpolation algorithm. These transformation values determine the final positions of an object's elements. The simplest form of interpolation for the creation of in-betweens is linear interpolation, which averages the parameters and supplies equally spaced in-between frames. However, this algorithm generally produces movement that appears jerky or abrupt because of discontinuous speed changes. More often the in-betweens are created using one of several possible curve or spline interpolation algorithms.

*Hierarchical animation*, the animation of hierarchical models, also often involves keyframing. In simple one-piece model keyframing animation, the animator positions the model, sets a keyframe, repositions the model, and sets another keyframe, at which point the system calculates and creates interpolated in-betweens (O'Rourke, 1998). In hierarchical animation, this process transpires for each node of the hierarchical model. Using the technique of *forward kinematics*, the transformations, or repositioning of the model's parts, are applied down the hierarchical tree. In order to get a desired positioning of all the parts – a keyframe – the animator must manually supply information about the transformations of each node of the hierarchical model. Though not conceptually difficult, when an intricate hierarchical model is used, this animation can become rather complicated and very time-consuming.

Luckily, the technique of *inverse kinematics* often can aid in the animation of certain hierarchical models, including human-like models. Using inverse kinematics, the propagation of transformations is reversed; the transformations are applied to the lowest level first, which then determines the transformation of the next level up, and so on, upward through the hierarchy. Thus, when the animator supplies the final position of an object – the keyframe – the repositioning of the objects above it in the hierarchy can be automatically computed by a computer animation system rather than manually supplied.

> If you had a human figure you wanted to make run, it would be a nightmare to first move a thigh, then a shin, and then a foot, all the while making sure these body parts were still aligned properly. IK allows you to simply move a single body part, and have the adjoining body parts move accordingly within a defined range of motion (Laybourne, 1998, p. 240)

When animating certain complex models, including humans and animals, it is helpful to use a *broken hierarchy*, which combines individual inverse kinematic chains (figure 17)

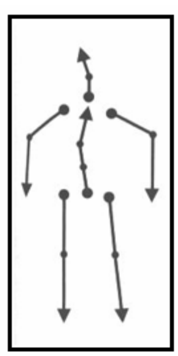


**Figure 17:** A broken hierarchy, O'Rourke (1998, p.165)

Furthermore, human and animal joints have restrictions in terms of the rotation of various joints. Therefore, inverse kinematics approaches are often combined with constraints on the rotation of joints in order to produced believable or realistic motion. The techniques discussed thus far have concerned the animation of relatively rigid objects. Here, the animator is concerned with transformation through translation, rotation, and scaling; the shape of the object, however, has remained stable.

Another set of kinematic and keyframing techniques involve shape animation, also called shape deformation. In *shape deformation*, rather than redefining the position and orientation of an entire object, an animator redefines the object's surface-defining points, thus altering the object's shape (O'Rourke, 1998). The key configurations of these surface-defining points comprise the keyframes, or *keyshapes.* The computer system then produces in-betweens using interpolation techniques. The sort of deformation, in which the keyframes consist of different versions of the same 3D model is often called *freeform shape deformation* (Kerlow, 1996). This process, even for a relatively simple change, can be very difficult and is nearly always time-consuming for the animator, because of the large numbers of points that must be redefined individually. Animators may at times use certain structures, called *external control structures*, which can simplify this keyshape definition process. For example, the animator may use a *lattice*, which is a 3D grid of points; each point of this lattice will be connected with a group, or cluster, of the surface-defining points. When using a lattice, the animator redefines these lattice points instead of redefining each of the individual surface-defining points.

Though the use of such structures can reduce the number of points the animator must control, thus reducing computational time, the use of these structures also diminishes the animator's ability to create very specific deformations, which may be desirable in certain situations. *Three-dimensional morphing*, a derivation of this shape deformation process, generally refers to the situation in which the keyframes, or keyshapes, consist of different models rather than different versions of one model, for example changing a human model to an animal model (Kerlow, 1996). Three-dimensional morphing may be desirable to an animator because it overcomes the following limitations of 2D morphing techniques: As a result of the lack of information regarding the object's spatial configuration, 2D morphing techniques are not able to appropriately handle changes in illumination and visibility (Lerios, Garfinkle, and Levoy, 1995). However, in 3D morphing, the best results occur when the models have the same number of surface-defining points, which requires a considerable amount of pre-planning, with regard to the models.

Because of the complexity involved with 3D morphing most of the high profile examples of morphing in film (for example, Terminator II and "Black or White") use 2D image morphing. Nevertheless, 3D morphing has been and remains an area of active research, and will likely become a more viable approach in the future (Lerios, Garfinkle, & Levoy, 1995; Kent, Carlson, & Parent, 1991).

## 4.2 Procedural Approaches

With *procedural*, or *rule-based*, motion generation techniques, the computer controls the motions of objects and characters based on a set of procedures or rules. *Particle systems* and *physically-based simulations* are the two most popular forms of procedural animation.   With regard to character animation, physically-based simulations are the most significant.

**<u>4.2.1 Particle Systems</u>**

Many phenomena, particularly natural ones, can not be easily modeled as surfaces; these systems are often modeled and animated using *particle systems.* Particle systems are commonly used for many types of natural phenomena, including smoke, gas, steam, mist, fire, clouds, snow, jets of water and water spray. When using a particle system, the animator defines a large number of small particles.

> A particle system is a large collection of individual elements, which, taken together, represent a conglomerate, fuzzy object. Both the behavior and appearance of each individual particle are very simple. The individual particles typically behave according to simple physical properties with respect to the environment but not with respect to other particles of the system. When viewed together, the particles create the impression of a single, dynamic, complex object. The illusion of a greater whole is referred to as emergent behavior (Parent, 2002, p.241)

In general, “particles have a life span during which they are created, behave a certain way, age, and die” (Kerlow, 1996, p.290). The animator of a particle system has a number of parameters to consider with respect to the characteristics of the particles in addition to the including *life span* or *lifetime*. The animator will likely define an *emission rate,* which is defines how many particles are emitted per during some time unit.   Other parameters an animator might control include the following: the speed of the particles; the source, where the particles are coming from; and, the spread, how much the particles fan.   Parameters of particle related to rendering include the following characteristics: color, transparency, blur, glow, and *trail life*, which defines how much, if any, of a visible trail is left by the particle.   Any or all of these parameters can be further adjusted through the addition of randomness. The use of particle systems to model and animate hair or fur is a recent somewhat unconventional application of particle systems. In these systems, the trail life is set to a sufficiently large value, so that the trail never disappears, creating the appearance of wirelike columns. Figure 18 shows some examples of hair and fur modeled animated by particle systems.

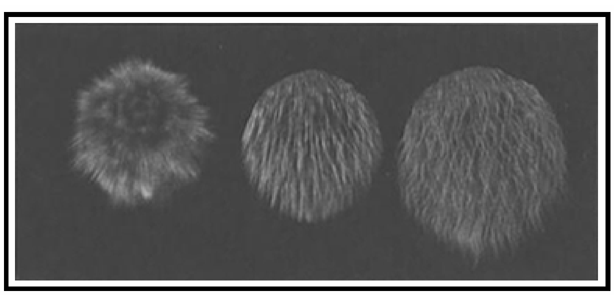


**Figure 18:** Hair and fur created with particle systems, O’Rourke (1998, p.225)

Another similar, but not identical, procedural technique is *flock animation*. Here the animator seeks to simulate the movements of large numbers of models in flocking, herding or schooling patterns. With flock animation, not only are the particles replaced by 3D models, these models also have more complex types of behavior, ones determined by both internal and external conditions (Kerlow, 1996). Collision avoidance within the flock is often a primary goal; however, if the flock is large, these collision detection and avoidance calculations can be quite time-consuming. Though flock animation is generally used to model flocks of birds, herds of animals, or schools of fish, they can also be used to model and animate crowds of people. As the techniques of flock animation do not necessary involve birds, these behaviors are sometimes referred to as *group behaviors* (Hodgins, O'Brien, & Bodenheimer, Jr., 1999). Both particle systems and flock behaviors may also be required to react to certain physical laws of the environment, e.g., gravity and wind.

### 4.2.2. Physically-Based Simulations

With *physically-based simulations*, the set of procedures or rules to generate motion are the laws of physics. The animator provides physical descriptions of the objects and information regarding the forces to be applied to the objects, which are related to the natural laws of motion. From this information a physically-based simulation can be generated, which is a simulation of "the motion that would result in the physical world if such forces were applied to a real object with specific characteristics" (Kerlow, 1996, p. 207). By sampling this physically-based simulation at a specific rate, the frames of an animation are produced.

The physical properties of an object include, most importantly, the mass, which is determined by the density and volume of the object. Additionally, the object's elasticity is also generally included, which is used to determine the rigidity of the object; this property is especially necessary if the object is expected to collide with other objects. *Elasticity* refers to the amount of energy lost when an object makes contact with something else. If an object is rigid, it loses a lot of energy, and it does not bounce far, if at all after a collision; if an object is flexible or elastic, it loses very little energy, and it bounces far after a collision. This physical description might also include the friction, both static and kinetic, created by an object. For a physically-based simulation, animators also need to describe the forces that act upon an object.

All forces acting on objects have a strength, or intensity, a direction, and, generally, a source. The most common, and most basic, force is gravity. Only in rare situations would gravity not affect all objects in a simulated environment. In actuality, the force of gravity on an object concerns the attraction between the Earth and that object. However, since the Earth is so much more massive than most objects on Earth, gravity essentially acts as a force pulling all objects downward, or towards it. Therefore, in physically-based simulations, gravity is generally defined as a simple force that pulls all objects downward at a specific rate (O'Rourke, 1998). Wind, fans, magnets and viscosity are further examples of forces. Furthermore, these basic forces can be used in combination to create more complex forces.

All of these forces can be categorized in a number of ways. Forces might be linear, point, or conical forces (Kerlow, 1996). A *linear force* acts on an object in one direction and at one strength at any given time; wind and gravity are examples of linear forces. With a *point force*, the force travels outward in all directions from a point, much like an exploding bomb. A *conical force*, like the force created by a fan, resembles a set of linear forces emanating in the shape of a cone from a single point. Forces can be local or global and act in an impacting, attractive, or resisting manner. *Global forces* have an affect all the objects in the environment, for example gravity. *Local forces*, however, affect only a certain set of objects or joints. Finally, forces can impact, attract, or resist objects. *Impacting forces* push objects away from the source of the force, such as wind, fans. *Attracting forces* pull the objects towards the source, as gravity does. *Resisting forces* provide opposition to an object moving through the environment, for example viscosity (Kerlow, 1996).

Many times the objects in an animation come into contact with one another and collide. In a successful physically-based simulation, the animator will likely need to include rules and procedures that govern the behaviors of collision detection and behaviors. The simplest method of dealing with collisions is to assume that the mass of an object is evenly distributed throughout it, and then aim the colliding forces at the geometric center of the object. Other methods involve the center of mass, as opposed to the geometric center, and the distribution of mass, allowing the simulation to take torque into account, which can result in more realistic motion. They are however, also, much more time-consuming (O'Rourke, 1998). Before the collision behaviors are used, the collisions must be detected.

> One of the most interesting and useful applications of motion dynamics animation techniques consists of detecting collisions between the objects that are being animated. Real objects react naturally to a collision by deforming and changing the direction and speed of their motion, and even breaking. Simulated three-dimensional models, however, will naturally ignore other objects that penetrate their space unless collision detection techniques are used. Using collision detection techniques can add a lot of processing time and expense to a scene because they must constantly check the position and dynamic properties of objects in order to avoid overlapping objects (Kerlow, 1996, p. 289).

To minimize calculations, an animator might define possible obstacles in the path of an animated object and then only do the collision detection, avoidance, and reactance calculations for those objects.

The physically-based simulations themselves can be divided into passive or active simulation systems. *Passive systems* move only when external forces act upon them, for they have no internal energy source; *active systems*, in addition to being moved by external forces, can also move of their own volition, for they do have an internal energy source (Hodgins, O'Brien, & Bodenheimer, Jr., 1999). Passive simulations have been used to animate clothes, hair, leaves, and pools of water. Many times, an animator will implement both types of systems (O'Brien, Zordan, & Hodgins, 2000).

## 4.3 Behavioral Approaches

*Behavioral approaches* for motion generation, the final category of model-based animation techniques, rely heavily on techniques borrowed from artificial intelligence, particularly robotics and expert systems. Here, the motion of the object or character results from modeling their cognitive processes.

In *goal-oriented* or *task-level systems*, the animator provides a goal or task for the character to perform, and the action is developed according to the fulfillment of this goal or task. This goal "for a character can be as simple as turning its head towards the light, or as complex as grabbing an object with the left hand, passing it to the right hand, and running out of the room while avoiding obstacles along the way" (Kerlow, 1996, p.293).

These goal-oriented systems are in a sense procedural, as they rely on a set of rules that allow a character to analyze and evaluate their environment in order to determine the best way of action given a task or goal. However, as these procedures deal primarily with the determination of a sequence of actions, rather than with the motion generation of those actions, these systems warrant a category of their own. These systems often include modules that take advantage of other motion generation techniques, such as inverse kinematics and physically-based procedural modules. These systems may also possess a learning component, where the character also has the ability to evaluate the results of an action and use these evaluations to better choose strategies in the future.

With full *behavioral systems*, the system also takes into account the character's individuality. These systems ideally take into consideration the following: different individuals perform the same type of action differently, and one individual performs the same action differently on different occasions. Thus, these behavioral systems take into account social and internal state variances.

Currently all forms of behavioral motion generation approaches exist primarily within academic research labs; and these systems are still yet general purpose (Magnenat-Thalmann & Thalmann, 1997). However, in the future, as these systems develop further, their usefulness will extend into commercial and entertainment realms as well. The consequences for the manner of production of computer-generated character animation could be considerable.

> For entertainment, the computer director will direct at the video screen synthetic actors, decors, lights and cameras using commands. If it is in real time, it will be like directing a real film but in a synthetic world. We will enter into the era of real computer-generated films, produced in a virtual world and directed by real human directors (Hegron, Palamidese, & Thalmann, 1989, p.7).

## 4.4 Motion Capture-Based Approaches

Using *motion capture-based* motion generation techniques, the animator accurately replicates motions from the real world. With these techniques, input devices, or *sensors*, are attached to a human actor in order to record the motion of that particular human. This kinematic information can then be used to generate the motion for a similarly structured model. The *sampling points* are the collection of points on the human actor where the sensors are placed. To use the data collected from motion capture, the animator must have set up a model, the virtual actor, with an appropriately similar hierarchy, so that its joints and structures can correspond with the sampling points on the human actor. The more sensors that are used, the more detailed the resulting animated motion can be; however, the more sensors that are used, the greater the computational and monetary costs become.

The placement of the sensors depends on many factors, including, the number of sensors available, the technology available, the type of motion to be captured, and so forth (Kerlow, 1996). Typically, the sensors are placed on the human actor's main joints,

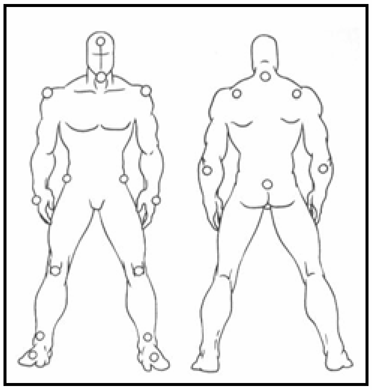


**Figure 19:** A configuration of 20 motion capture sensors on a human actor, Kerlow (1996, p. 279)
**Figure 20:** A motion capture system using optical sensors, Parent (2002, p.370)

in addition to other locations that aid in capturing orientation and movement. Figure 19 shows a configuration of twenty motion sensors.

Currently, the two most popular classes of motion capture sensors are magnetic and optical ones. *Magnetics*-based motion capture involves the use of a centrally located transmitter and a set of receivers (the sensors) that detect magnetic fields in order to measure the sensors' spatial relationships to the transmitter. These sensors are attached by cable. The *capture area*, the area in which the human actor can move, must not be near any sizable area of metal, for such an area might affect the surrounding magnetic fields, distorting the motion capture data. In *optical*-based motion capture the sensors are reflective markers, and a series of cameras records the data by detecting the light that bounces off the reflectors. Figure 20 shows a human actor with optical sensors.

In terms of freedom of motion for the human actor, optical motion capture systems are better because there are no cables or cords to hinder and restrict movement. There are wireless magnetic receivers; however they are currently much more expensive than the other options (Parent, 2002). Optical motion capture systems also have a slightly larger capture area than its magnetic counterparts. Magnetic motion capture systems can provide real-time feedback, whereas optical motion capture systems can not. Magnetic motion capture systems also do not suffer from the problem of occlusion that optical motion capture systems often do; in optical systems, the human actor or props can occlude, or hide, sensors from the view of sensors. Though typically used to record larger human body movements, motion capture techniques have also been used to capture data on facial expression animation.

## 4.5 Comparison and Choice of Technique

An animator's choice of motion generation technique may depend on a number of characteristics. Within animation for entertainment and character animation, motion capture-based techniques and keyframing/kinematics remain the most common techniques. Procedural methods are, however, gaining in popularity. Additionally, many animators use hybrid animation systems, in which different animation techniques are applied to different parts or aspects of an object or environment. The following comparison of computer based motion generation techniques will focus on techniques most relevant to character animation, and will consider the issues of ease of use, cost, ability to create realistic animation, generalizability, complexity of animation, and animator control.

Using motion capture, an animator can cost-effectively and relatively easily record human motions for use in animations. Since the motion is captured directly from reality, they have a high degree of realism, and the motions can encapsulate the subtleties of human motion that are often so difficult to portray with other techniques. “When humans move, their limbs and joints almost constantly change position in very irregular and subtle ways, and the generalization of movement that results from an interpolated-motion curve often does not convey the idiosyncratic ‘human-ness’ of that movement” (O’Rourke, 1998, p. 213). However, the movements produced through motion capture are not easily generalizable.

> The motion and the actor must exist prior to the synthesized result. Even if we recorded thousands of individual motions and retrieved them through some kind of indexed video, we would still lack the freshness, variability, and adaptability of humans to live, work, and play in an infinite variety of settings (Badler, Phillips, & Webber, 1992, p. 2).

Furthermore, because the motion capture sensors are set up in a network and have a limited range, the motions to capture must be able to be performed in a relatively confined area. Motion capture is most often used for human motion. The use of motion capture for other animals’ movements faces the inherent difficulties of attempting to direct animals to perform specific activities at specific times.

Using procedural methods, particularly physically-based simulation, the animator moves an object or character according to a set of rules or procedures. These methods are advantageous for the animation of systems that would be ridiculously complex and impractical to animate by hand, including particle systems, flock animation, or other animations requiring a large number of interrelated objects. Large amounts of subtle motion, such as the leaves and branches of a tree moving in the wind, are difficult to model convincingly using other approaches. Physically-based simulations are often the best option for highly realistic synthetic human motion. “Only modeling of objects that move under the influence of forces and torques can be realistic” (Thalmann, 1996, p. 2). These methods also allow the animator to produce a family of similar movements with relative ease; these allow for some degree of generalizability and reuse.

Procedural approaches also allow for an increased degree of automation; once the initial information about the object’s physical properties and the forces acting on the object are input by the animator, the production of the animation is determined solely by the rules and procedures through simulation. However, at this point in the development of these systems, an animator usually requires a strong background and understanding of the laws of physics in order to animate using procedural and physically-based simulation systems. “Unfortunately, building a new simulation is sometimes difficult process requiring an in-depth understanding of the relevant physical laws. Once a simulation has been designed, however, the animator may use it without understanding the internals of the simulation” (Hodgins, O’Brien, & Bodenheimer, Jr., 1999, p.6). Additionally, these pre-determined set of procedures for motion control limit an animator’s fine control of a motion; thereby, these procedures also limit an animator’s ability to add individuality and/or expressiveness to a character’s behaviors and movements.

On the other hand, kinematic/keyframing approaches, which rely more heavily upon the animator's input of geometric data, provide the animator with much finer control of an object's motion. However, the produced motions are not as easily generalizable as motions produced by procedural methods are. Though the creation of realistic, or believable, motion is possible in kinematic/keyframe systems, it is not an easy task, for it, "Requires that the animator intimately understand how the animated object should behave and have the talent to express that behavior in keyframes" (Hodgins, O'Brien, & Bodenheimer, Jr., 1999, p. 6). Nonetheless, "Kinematic models have been used in many applications, mainly in the entertainment area, since they are easier to use and not so time-consuming" (Hegron, Palamidese, & Thalmann, 1989, p.3), and allow for fine control of motion.

## 5. THE QUEST FOR REALISM

Research on certain animation techniques often have as a primary goal the production of highly realistic animation, particularly the research on procedural and behavioral approaches. In animation, one may regard "realism" in two respects. First, realism can refer to the degree to which each image or frame of the animation is photo-realistic, or indistinguishable from a real photograph. Second, realism can also refer to the nature of the movement created in the animation. An animated object character that may not be photo-realistic can still move (e.g. fall, fly, walk, run, dance) in a realistic manner, specifically moving exactly how that object or character would were it real.

Though entertainment animators traditionally have focused on the latter, as technology and techniques develop, computer animation researchers and some entertainment animators alike have been striving for a combination of the two. The use of traditional animation techniques or hand-drawings to create a completely realistic animation of any meaningful complexity would be highly impractical, if not virtually impossible, given the skill needed to make just one completely photo-realistic drawing. The computer-generated creation of a single image that is completely photo-realistic, though difficult in its own right, is not the crux of the computer animator's difficulty with realistic animation. The animator must create a large series of such images, which when displayed produce a realistic illusion of motion.

Given this difficulty in producing completely realistic animation, the success of the animation industry, both traditional and computer, has instead been the result of the creation of successfully stylized, or caricatured, animated worlds and characters. Within these worlds, animation works best when it is still "believable."

> Cartoon characters are hardly "real," yet we watch them and properly interpret their actions and motions in the evolving context of a story…they are not 'realistic' in the physical sense – no one expects to see a manifest Mickey Mouse walking down the street. Nor do cartoons move like people – they squash and stretch and perform all sorts of actions that we would never want to do. But somehow our perceptions often make these characters *believable* (Badler, Phillips, & Webber, 1993, p. 2).

Though the motions of most animated characters are not completely realistic, they ideally have a degree of naturalness to them; their motions are often exaggerations of real motions. Real motion is fluid, and in animation, jerky movement is generally considered disconcerting and lacking in believability or naturalness.

If, however, one wanted to animate a character with a highly human appearance, the audience unconsciously places increased demands on the motion of that character. "The audience's preconceptions are important. If your audience sees a picture-perfect digital human on the screen, it will expect him to walk, talk, and act like a human. If he's the slightest bit off from the way a real human acts, the illusion is lost" (Maestri, 1999, p.7). In other words, humans are experts on their own movements, and they will closely scrutinize movements from any character that looks like them. The task of building a photo-realistic digital human with highly realistic movement is a daunting one. "A holy grail of computer animation is to produce a synthetic human character indistinguishable from a real person" (Parent, 2002, p. 27). A smaller but more common goal, though still exceedingly difficult, would be to just create realistic human motion and behavior. Currently, the primary method for completely realistic human-like motion, at least within entertainment animation, is motion capture. However, since the motions generated thusly are not generalizable, a significant amount of research is geared towards developing models and motion generation techniques that allow for highly realistic human-like animation. Researchers at the University of Pennsylvania describe their goal: "We seek to build computational models of human-like figures which, through they may not trick our sense into believing they are alive, nonetheless manifest animacy and convincing behavior" (Badler, Phillips, & Webber, 1992, p. 3).

Since successful character animations have been created, both traditionally and by computer and given the extensive barriers, why is the drive to create highly realistic digital humans so large? Surely, the intellectual curiosity involved in digitally cloning ourselves may be a draw for some. However, more importantly, the creation of digital humans that move and behave according to environmental constraints as real people would be of significant practical use. Useful tests, but dangerous tests, of product safety could be done in digital worlds without risking the safety of actual humans. If these completely realistic synthetic humans one day become available, they may not, however, have great appeal within the realm of character animation,

> If an animated character moves *exactly* like a real human, and especially if that character is modeled and rendered very realistically, it may lose all visual and aesthetic interest. Character animation, like any art form, is interesting to the viewer because it is an *interpretation* of the way we behave. If an animation replicates our behavior too exactly, it may lose the appeal of animation and become a dry simulation (O'Rourke, 1998, p.213)

When animators intend to make animations where success is gauged by the ability to tell a story using engaging and endearing characters, full of emotion and personality, a high degree of realism is not necessarily a prerequisite. These animations, whether drawn by hand or computer-generated, are an art form, and thus share certain principles, although the application thereof may differ somewhat.

## 6. THE ART OF ANIMATION

John Lasseter, of Pixar, was initially trained in traditional animation before becoming an Academy Award-winning computer animator. He wrote an article describing the application of traditional animation principles, as originally developed by Disney in the 1930s, to 3D computer-generated character animation. He says,

> Whether it is generated by hand or computer, the first goal of the animator is to entertain. The animator must have two things: a clear concept of exactly what will entertain the audience; and the tools and skills to put those ideas across clearly and unambiguously. Tools, in the sense of hardware and software, are simply not enough. The principles … are tools as well, tools which are just as important as the computers we work with (Lasseter, 1987, p. 43).

Successful animation as gauged by an audience does not necessarily require completely realistically animated characters, but it does always require characters with personality. Characters are individuals. Animators are taught that no two people walk the same, therefore their animated characters, human or otherwise, should not walk the same either. Additionally, any character will walk differently on different occasion dependent on its physical state, including age, and emotional state, e.g. happy, sad, angry, or stressed. This applies regardless of media.

The early animators at Disney isolated and named procedures that they had developed through their work. These procedures became the fundamental principles of traditional animation. The process through which the principles were developed, and the principles themselves, are described in <u>The Illusion of Life: Disney Animation</u> (Thomas and Johnston, 1995). They are as follows, in alphabetical order:

1. *Anticipation* – The preparation for an action
2. *Appeal* – The creation of a design or an action that the audience enjoys watching
3. *Arcs* – The path of action for natural motion
4. *Exaggeration* – The emphasis of an idea through exaggeration of a design or an action
5. *Follow Through and Overlapping Action* – The termination of an action and the flowing of actions into one another
6. *Secondary Action* – The action of an object that results from another action; is usually a support for the main action
7. *Slow in and Slow out* – The method of spacing in-between frames to achieve subtlety of timing and movement, particularly in accordance with physical laws
8. *Squash and stretch* – The distortion of an object’s shape during an action, especially a collision; this distortion defines the rigidity and mass of the object
9. *Staging* – The presentation of an idea so that it is completely and unmistakably clear
10. *Timing* – the spacing of actions to define weight, size, and personality of an object or character

All of these principles are pertinent to 3D computer-generated character animation; the application of some of the principles, however, has changed due to the difference in media. Furthermore, some of the principles are incorporated into, and occasionally constrained by, certain motion generation techniques.

The fundamental principles of animation all attempt to achieve certain goals related to a successful character animation. The usage of these principles can be considered with regard to these goals. There are three such goals.

First, several of the principles address the goal of imbuing a physical basis to an object; specifically, these principles address the *physical representation* of an object. As discussed in the preceding section, animated motions need not be completely realistic, but they do need to be believable. An object or character's motion that seems jerky or otherwise unnatural is often disconcerting to the viewer and will undermine the story-telling goal of character animation. Part of creating a believable motion is imbuing the object or character with a physical basis or representation.

Second, some of the principles address the goal of an effective *presentation of actions* to the audience. This occurs both through visual clues and through the compositions of scenes. The viewer of an animation is not able to watch all parts of the screen at all times. Therefore, in order to successfully present all of the necessary building blocks of a storyline, the animator must ensure that the viewer watches the appropriate parts of the scene at the appropriate times.

Third, some of the principles address the goal of the *use of action* by the animator in order to create certain overall desired effects for the audience, in particular the creation of successful characters. Successful character animations need successful characters. These successful characters are ones that have personalities; the audience should be drawn to these characters. The audience is drawn to the characters through the detection of emotions and thought processes, elements that the animator must provide through the actions and movements of the objects and characters.

Each goal may utilize more than one principle. The following sections will consider each of these three goals in turn, addressing how these principles achieve the goals, and how certain commonly used 3D computer motion generation techniques relate to these principles, particularly keyframing/kinematic, physically-based simulation, and motion capture techniques.

## 6.1 The Physical Representation

Part of the creation of believable motion is imbuing the object or character with an appropriate physical representation. In other words, objects and characters in the real world possess mass and other physical characteristics, and to create believable motion these characteristics should be reflected in the animation. Some of the principles of fundamental animation address the construction of the physical basis of an object or character. Without the believable motion that results from the application of these principles, the motion may seem rough or otherwise unnatural. Thus, the resulting animation will often be disconcerting to the audience, which can undercut the primary story-telling goal. The principles that deal with the object's physical representation are squash and stretch, timing, slow in and out, arcs, secondary action, anticipation, and follow through.

The use of certain computer animation systems has made some of these principles less overtly relevant, for they are covered more or less automatically by the animation system. This is particularly the case for those systems that utilize physically-based simulations, the procedural motion approach described in section 4.2.2. The underlying concepts, however, still apply in all cases.

*Squash and stretch,* which the Disney animators called the most important discovery, refers to the distortions of an object in motion order to define its mass and rigidity.

> The squashed position can depict the form either flattened out by great pressure or bunched up and pushed together. The stretched position always shows the same form in a very extended condition. The movement from one drawing to the next became the very essence of the animation (Thomas & Johnston, 1995, p.48).

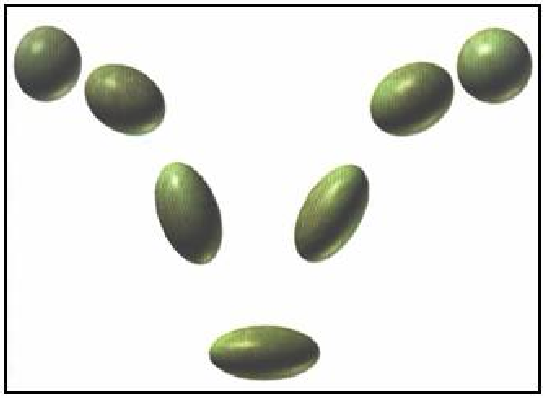


**Figure 21:** The classic example of 'squash and stretch,' the bouncing ball, Ratner (1998, p. 185)

The bouncing ball is the classic example of squash and stretch (figure 21). With character animation, the most obvious usage is muscles: When a muscle contracts it squashes, when the muscle extends it stretches. Vital to this principle is the rule that, no matter how distorted an object becomes, its volume remains constant.

With most computer animation techniques some sort of model is typically involved. Whether that model was created using surfaces, solids, or geometric primitives, this use of models often aids in the assessment of volume maintenance. With physically-based simulations, the animator mathematically defines the object's mass and the appropriate forces, and the system will calculate the appropriate distortions, including maintenance of volume. In this case, however, though it simplifies or automates the animator's role, this method of physically-based simulation also makes using exaggeration of distortion for effect more difficult.

Behavioral systems would likely face a similar drawback. Chenney, Pingel, Iverson, and Szymanski (2002) attempted to create a hybrid animation system that allows for increased squash and stretch control while also possessing the benefits of physically-based simulations. Motion capture techniques involve collecting data regarding positions of joints and body parts, but are limited in the information that they can provide about volume, and, hence, volume conservation. Squash and stretch is also very important in facial animation, particularly in terms of showing the relationship between parts of the face during different facial expressions (Lasseter, 1987).

*Timing* is the speed of action, and it can reflect the physical qualities of the animated object. Timing can affect the perception of mass. A heavier object takes a greater force and a longer time to accelerate and decelerate.

> Think of a simple sphere sitting on the ground … Is it a bowling ball or a basketball? Until it moves, you have no idea whether the sphere is filled with air

> or lead. Once the sphere is in motion, however, its characteristics become apparent. A bowling ball is heavy. It moves slowly, and a great deal of force is required to change its direction. A basketball, on the other hand, is relatively light. It moves fast, bounces easily, and it takes very little force to change its direction (Maestri, 1999, p. 177).

With physically-based simulations, the animation system will calculate the timing by providing the positions over time of the objects based on the given physical properties and laws. For keyframing/kinematic techniques, timing is a more conscious process in that the animators must deliberately choose the number and spacing of keyframes, which consequently affects the pace of the action. With motion capture techniques, the timing is determined automatically by the human actor's motions.

In nature, as the result of physical properties and laws of natures, objects move in particular ways. First, objects generally accelerate into and decelerate out of a position or pose. *Slow in* and *slow out* refer to the timing of in-betweens in order to achieve this acceleration and deceleration. Second, objects in nature generally move not in straight lines but in *arcs*, as it is the most economical path. Arcs are used extensively in animation describe the visual paths of action. "Very few living organisms are capable of moves that have a mechanical in and out or up and down precision…. The head seldom thrusts straight out, then back again; it lifts slightly, or drops as it returns" (Thomas &

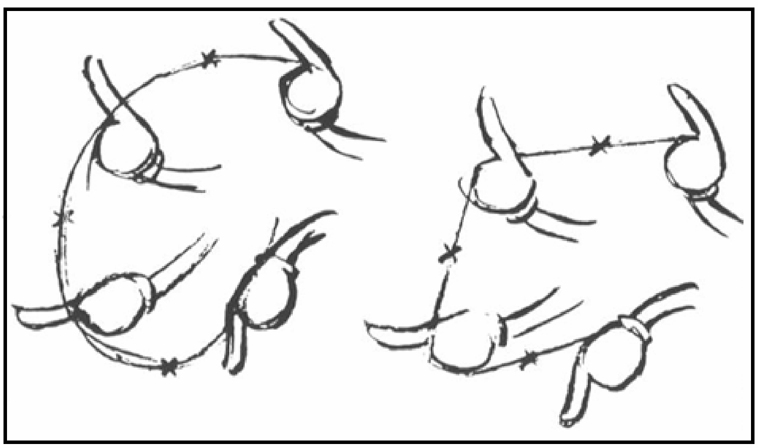


**Figure 22:** Arcs and visual paths of action, Thomas and Johnston (1995, p.62)

Johnston, 1995, p. 62). Figure 22 shows the dramatic effect the use of arcs versus straight lines can have on the motion of a hand gesture. In keyframing/kinematic systems, slow ins and outs are generally accomplished through the interpolation of the timing according to a curve or spline, and arcs are generally accomplished through the interpolation of the position of the object according to a curve or spline. In physically-based simulations, the animation system will produce slow ins and outs and arcs as a byproduct of applying the laws of physics and natural motion. With motion capture techniques, these elements are determined automatically by the human actor's motions.

Other principles related to instilling an object with a physical basis include secondary action, anticipation, and follow through. Newton's third law of motion tells us that for every action, there is an equal and opposite reaction. *Secondary actions* in animation are the following: actions of objects that result from the main action, or the smaller actions that complement the main action. These secondary actions may involve physically-based reactions, which would add a realistic complexity to the animation. In kinematic/keyframing systems, the animator would need to separately provide geometric information and positions of any additional objects involved in the secondary actions. In a physically-based situation, if the animator has provided rules or procedures for collision detection and behavior, the secondary action would be produced automatically as a result of the application of these rules. Motion capture systems generally only provide information on the main action.

*Anticipation*, the preparation for an action, is in one sense the anatomical preparation for action, without which many actions would appear abrupt and unnatural.

> Few movements in real life occur without some kind of anticipation. It seems to be the natural way for creatures to move, and without it there would be little power in any action. To the golfer, it is the backswing; to the baseball pitcher it is his windup" (Thomas & Johnston, 1995, p. 53).

At the other end, just as actions do not start abruptly, they do not end so either. *Follow through* refers to the ending of the action. For the baseball pitcher, once he releases the ball, his arm does not stop, but continues past the point of release. The way in which the object slows down during this follow through can also indicate weight.

## 6.2 The Presentation of Actions to the Audience

Several of the principles of traditional animation address the presentation of the action to the audience, both through visual clues and through the organization of the scene. The audience of an animation will not be able to watch all parts of the screen at all times. In order to successfully tell a story, the animator must ensure that the viewer watches the appropriate parts of the scene at the appropriate times. The principles that pertain to this issue are among principles developed long ago in theater, and then eventually used in live-action films. Generally, these principles apply similarly to traditional and computer animation; here, the application of the principles vary less with the different motion generation techniques that the applications of the principles in the previous section did. The principles that deal with this issue of presentation of action are anticipation, staging, timing, exaggeration, and overlapping.

Anticipation, the preparation for an action, is used to guide the attention of the audience so that they do not miss an important major action.

> This anticipation can be as small as a change of expression or as big as the broadest physical action. Before a man runs, he crouches low, gathering himself like a spring, or, the reverse, he draws back in the opposite direction, raising his shoulder and one leg, as he aims himself at the place of the next activity (Thomas & Johnston, 1995, p. 52)

Anticipations often precede most of the main actions in a scene. Anything action the animator produces can be preceded by an anticipation action. A properly timed

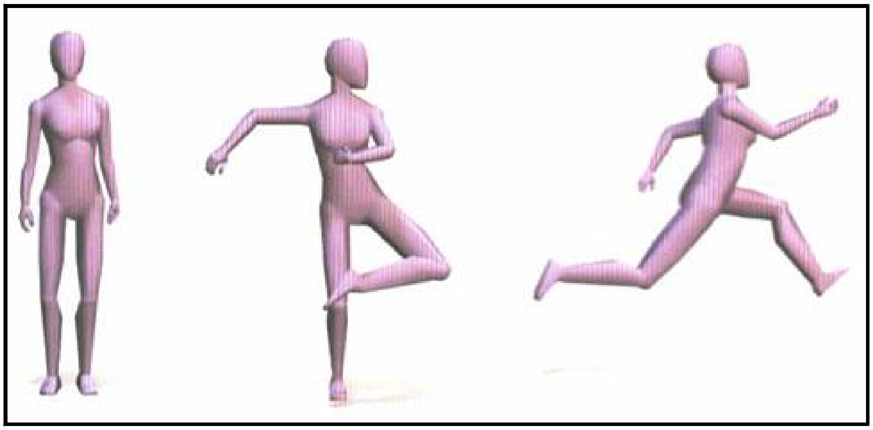


**Figure 23:** The principle of anticipation, Maestri (1999, p.191)

anticipation can better prepare the audience for a quick action (figure 23). Often times, animators use large anticipation actions to precede quick actions. Keyframing/kinematic approaches allow for the greatest control of anticipation actions. Physically-based simulation and other procedural approaches will often constrict the range of anticipation actions with regard to laws of physics and the physical characteristics of the animated object. In motion capture based actions, anticipation is determined solely by the actions of the human actor.

Closely related to anticipation is *timing*, which is also important to the presentation of actions. Spending appropriate amounts of time on the anticipation of the action, the action itself, and the reaction, or follow through, to the action, are critical to creating readable actions. The animator must ensure that the action is not too fast, so that the audience does not miss it. The animator must also ensure that the action is not so slow, so that the audience's eyes start to wander.

*Overlapping* involves the timing of multiple actions so that they intersect with one other; this principle is closely tied to anticipation, timing, and follow through, and is an aid in the creation of a scene that appears to continually evolve (Parent, 2002). Again, keyframing/kinematic approaches allow for the greatest fine control of the timing of actions. Physically-based simulations often restrict the ability of the animator to exaggerate the length of the anticipatory or follow through actions for presentation's sake. In motion capture-based methods, the timing of is determined solely by the actions of the human actor.

*Staging* is a general principle with a specific meaning: The presentation of an idea so that it is completely and unmistakably clear. This idea might be an action, a personality, an expression, or a mood. The overall intent is clear communication. Regardless of the animation technique, this principle relies on the animator to stage a main action so that it is perceivable, understood and not distracted from by other portions of the screen. Generally, the animator wants to time the animation such that the main actions are presented one at a time. Furthermore, the animator generally wants those main actions to contrast from the rest of the scene. Secondary actions should be kept subordinate to the main action, so as not to distract from the most important actions.

> You make the drawings that will stage each idea in the strongest and simplest way before going on to the next action. You are saying in effect, "Look at this – now look at this – and now this." You make sure the camera is the right distance from

> the character to show what he is doing. If he is kicking, you do not have the camera in close on a waist shot. If you are displaying your character's expression, you do not do it in a long shot where the figure is lost in the background (Thomas & Johnston, 1995, p. 56).

Part of staging involves the posing of characters. If a pose can be interpreted in a black

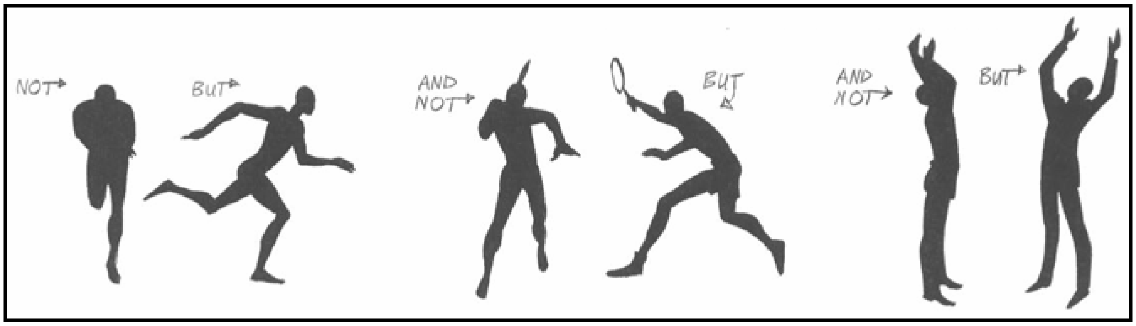



**Figure 24:** Creating strong poses using silhouettes, Williams (2001, p.251)

and white silhouette, it aids in readability, and is usually to the animator's benefit (figure 24). In the early days of animation, when characters were all in black and white, the only way to delineate limbs or other parts of a model was through descriptive silhouettes. Despite the addition of grayscale and color, descriptive silhouettes and strong poses are still useful in making actions and poses more readable for the audience. Certain features of 3D environments in computer animation can aid in the creating readable poses. For instance, shadows, automatically produced as the result of the lighting of models, can aid in readability of poses. In motion capture systems, the poses are determined by the human actors, though the camera angle of the animation can be changed so as to provide a more readable view of the pose. Kinematic/keyframing and procedural approaches also possess this ability to position cameras in order to allow for more readable poses. Kinematic/keyframing approaches provide finer control of the action than physically-based simulations do. This finer control in the positioning of parts allows the animator using a kinematic/keyframing approach to more easily manipulate the pose for readability's sake.

Suitable *exaggeration* of motion can also be an effective tool in directing the eye to the appropriate actions. Exaggeration will be discussed more in the following section.

### 6.3 The Use of Actions to Create Desired Overall Effects

Several of the fundamental principles of traditional animation address the animator's use of actions to create desired effects in the audience, in particular the creation of successful characters. The creation of a successful character animation requires the creation of successful characters, which are characters that have appealing personalities. The audience of the animation should be drawn to these characters, in part, through the emotions and thought processes imparted by the animator through the use of certain fundamental principles. The principles involved with this category include timing, exaggeration, squash and stretch, and appeal.

Timing is crucial in implying the emotional qualities of characters. Often the timing is more important than the appearance of a character with regard to imparting emotional qualities. Timing gives meaning to the movement, incorporating both tempo and rhythm; it gives the audience a sense of why an object is moving. "The varying speed of those movements determined whether the character was lethargic, excited, nervous, relaxed. Neither acting nor attitude could be portrayed without paying very close attention to Timing" (Thomas & Johnston, 1995, p. 64). Keyframing/kinematic systems provide the greatest ability to vary the timing in order to meet this goal. In physically-based systems, the timing of an object is based primarily on its physical properties and the forces of physics that act upon that object; in these systems, varying the timing of an action to suit purposes other than realism is difficult.

In addition to highlighting motions, exaggeration can also be used to highlight emotions and/or increase those emotions' impacts. Exaggeration, though commonly used and highly effective, is not to be used arbitrarily.

> He [Walt Disney] believed in going to the heart of anything and developing the essence of what he found. If a character was to be sad, make him sadder; bright, make him brighter; worried, more worried; wild, make him wilder. Some of the artists had felt that "exaggeration" meant a more distorted drawing, or an action so violent it was disturbing. They found they had missed the point (Thomas & Johnston, 1995, p. 65).

Squash and stretch can also be used to exaggerate the motion. The use of exaggeration of various components of the scene should be balanced as well; the balance of exaggerated and naturalistic components can make a scene believable and realistic in addition to gaining the benefits of exaggeration (Lasseter, 1987). The use of physically-based methods can restrict the animator's ability to produce actions that differ even slightly from actions based on the laws of physics and the physical characteristics of the animated object. Keyframe/kinematic methods are better suited for an animator who wants to use exaggeration, as these methods they rely less on automated actions, and allow for increased animator fine control.

*Appeal* in a character describes a quality that is equivalent to charisma in a live actor. To Disney's animators it meant anything that the audience liked to see, including charm, pleasing design, simplicity, communication, and/or magnetism (Thomas & Johnston, 1995). The audience, though, may not necessarily be able to identify the exact aspect of an animation that is appealing; appeal comes in more forms than "cuddly bunnies and soft kittens."

> Your eye is drawn to the figure that has appeal, and once there, it is held while you appreciate what you are seeing. A striking, heroic figure can have appeal. A villainess, even though chilling and dramatic, should have appeal; otherwise, you will not want to watch what she is doing. The ugly and repulsive may capture your gaze, but there will be neither the building of character nor identification with the situation that will be need (Thomas & Johnston, 1995, p. 68).

Weak drawings, unreadable actions, poor design, clumsy shapes, awkward movements all reduce appeal. Appeal is important when posing characters, itself a key element of staging.

These fundamental principles of animation are ultimately all interrelated, and when used properly, can impart a consistent, pleasing overall aesthetic. Appeal of the animation as a whole also refers to the overarching consistency, balance, and symmetry of elements in the scenes. If the objects and characters in an animation are all complex, the addition of a relatively simple object or character would throw the animation off balance, and vice versa. If the objects, characters and their movements in an animation are all highly realistic, the addition of a relatively stylized object, character or movement would also throw the animation off balance, and vice versa. Unless this lack of balance is part of the story line (that is, the jarring effect is desired), the overall consistency of an animation should be kept. More equal numbers of the complex versus simple, realistic versus stylized, may also produced a balanced overall appeal.

These fundamental principles of animation, more importantly, can and should also be used to impart personalities to the characters. These personalities should not be an afterthought. They should be considered from the beginning when constructing the model and when constructing each action. No two characters should do the same action in the same fashion, nor should one character do a particular action in the same fashion when in different emotional states (Lasseter, 1987). Even if an animator creates a completely realistic modeled character that also moves realistically, for effective storytelling, there must also be some way to alter the motion on different occasions. That character should be able to appear happy, sad, tired, and so forth, all of which are expressed through their actions.

> When character animation is successful and the audience is thoroughly entertained, it is because the characters and story have become more important and apparent than the technique that went into the animation. Whether drawn by hand or computer, the success of character animation lies in the personality of the characters (Lasseter, 1987, p. 43).

Keyframe/kinematic systems, which are based on traditional hand-drawn animation, are currently are better suited to the generation of characters with these characteristics than systems based on procedural methods are. Physically-based simulation allows for some automation in the creation of animation, but animators lose control of the fine details of motions, details which are used to portray emotions, expressiveness, individual differences, and, hence, personality.

> [Traditional] animators are expert at conveying information through moving imagery, be it the personality of a character, their actions, or the elements of a story… Users have traditionally faced a choice between the high-quality, high-cost of hand animation and the lower-quality, interactivity of simulation motion (Chenney, Pingel, Iverson, & Szymanski, 2002, p.133).

## 6.4 Computer Animators as Artists

Though their techniques may differ vastly, both the traditional and computer animators of character animation are artists. Animation is an art, an art that involves the creation the illusion of motion. Computer animators may or may not have a background in traditional animation. They both, however, benefit from similar studies. Both benefit from studies of anatomy, physiology, and biomechanics. The study of anatomy may include reference books or more traditional "artistic" resources, such as life drawing classes.

Consider the common wooden artist's mannequin (figure 25 on following page) and computer generated model used to introduce the basics of figure construction in Ratner (figure 26 on following page). Whereas traditional animators might use their knowledge of human anatomy to visualize the internal structure of their animations, computer animators might use this same knowledge to actually model the human anatomy, a model that they will then animate.

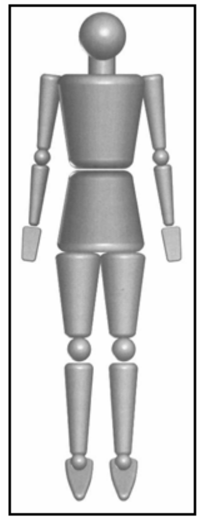



**Figure 25:** A wooden artist's mannequin
**Figure 26:** A computer generated human model, Ratner (1998, p.15)

## 7. CONCLUSION

This paper began with a comparison of the first filmed animation from 1906, Humorous Phases of Funny Faces (figure 27) done using chalk, with the recent 2001 animation Monsters, Inc. (figure 28), a computer animation that utilized many of the latest technology and techniques. This comparison highlighted the radical development


**Figure 27:** Humorous Phases of Funny Faces (1906), J. Stuart Blackton
**Figure 28:** Monsters, Inc. (2001), Disney/Pixar

of animation techniques that has occurred in the past century of animated film history. The historical highlights of traditional animation and computer animation given should have provided a context for the development and comparison of various computer animation techniques. A number of these techniques have developed not only to ease the process of animation, but also to provide increasingly remarkable degrees of realism.

However, the role of realism within character animation is, by far, not the most important element of triumphant and absorbing animated storytelling Traditional character animation did not reach its heyday until the animators at Disney developed and refined procedures that made use of certain fundamental principles, principles which when executed properly imbue the characters with personality and tell a fluid and compelling story. Successful computer-generated character animations utilize these same principles. Monsters, Inc. and Shrek were not remarkable solely for their advances in degree of realism. They would not have been nearly as successful had they not contained engaging characters, full of personality and emotions, which were as often as not conveyed through motion.

Some computer animators paint a grim view of the link between traditional and computer animation. They predict that eventually, the creators of computer animations will direct synthetic actors, lights, cameras, and so on, in a virtual using higher level commands much like a film director would. If this were the case, the techniques in computer animation that are extensions of traditional animations, including keyframing, would become obsolete. The low-level creation the illusion of motion in such a system will no longer rest in the animator's hands, who would no longer define motion, but who would instead define behaviors.

Furthermore, some traditional animators, there is a fear that computers will take control, and possibly even replace, the traditional animation process (Culhane, 1990). The computer animation technology and techniques are not so advanced as to allow human directors to direct animation as they would a film, even less so if these animations require many characters with personality and individuality.

Were such systems ever to be available, many animators, of both forms, would still contend that it would be highly unlikely that computer animation's presence would eliminate the traditional animation process. One might consider this traditional animation process in two regards: one, the principles developed, refined, and used by traditional animators with the artistry of traditional animation, and two, the actual hand-drawing of the frames of an animation. Computer animation technology will not eliminate the need and desire to use exaggeration, staging, timing, anticipation, and appeal, among others, to create engaging character animations. It may alter the way in which the principles are applied. Even so, there are likely to remain computer animators who enjoy the fine control of these principles that keyframing systems allow, systems which mimic the traditional animation process.

Not all those enamored with animation are also enamored with the computer, and although they might use the computer to aid the composition process, animators who prefer to create the personalities of characters through drawing are unlikely to disappear. A few painters at the dawn of photography feared that that technology would render their art obsolete; though, perhaps, the role of painting changed to an extent, painting is still a major art form. Rather, animators in general should consider the computer as another tool, and like other tools have nothing intrinsically creative about them, they rely on the artist to conceive of effective methods to use these tools.

Successful computer character animation requires much more than realistic simulation and has much to take away from the study of and use of principles developed over decades of traditional animation creation.

"Animation can explain whatever the mind of man can conceive. This facility makes it the most versatile and explicit means of communication yet devised for quick mass appreciation."
Walt Disney

## REFERENCES


Bringing drawings life: The Xerox and C.A.P.S. Systems. (n.d.). Retrieved February 15, 2003, from Golden Gate Disneyana Club Web site: http://www.ggdc.org/mp-100xerox.htm

Badler, H.I., Phillips, C.B., & Webber, B.L. (1993). Simulating humans: Computer graphics, animation, and control. New York: Oxford University Press. Retrived online version December 15, 2002, from http://www.cis.upenn.edu/~badler/book/book.html

Boulic, G., Magnenat-Thalmann, N., & Thalmann, D. (1990). Human free-walking model for real time interactive design of gaits. In N. Magnenat-Thalmann & D. Thalmann (Eds.) Computer Animation '90 (pp. 61-79). New York: Springer-Verlag.



Bringing drawings life: The Xerox and C.A.P.S. Systems. (n.d.). Retrieved February 15, 2003, from Golden Gate Disneyana Club Web site: http://www.ggdc.org/mp-100xerox.htm.



Chenney, S, Pingel, M., Iverson, R., & Szymanski, M. (2002). Simulating cartoon style animation. Proceedings of Non-Photorealistic Animation and Rendering (NPAR), 133-138.

Culhane, S. (1990). Animation: From script to screen. New York: St. Martin's Press.

Furniss, M. (1998). Art in motion: Animation aesthetics. Sydney, Austrailia: John Libbey.

Hegron, G., Palamidese, P, & Thalmann, D. (1989). Motion control in animation, simulation and visualization. Computer Graphics Forum, 8, 347-352. Retrieved online version January 15, 2003, from http://ligwww.epfl.ch/~thalmann/papers.dir/CGF.motion.pdf

Hodgins, J. K., O'Brien, J. F., & Bodenheimer, R. E. (1999). Computer Animation. In J.G. Webster (Ed.), Wiley Encyclopedia of Electrical and Electronics Engineering, vol. 3, 686-690. Retrieved December 1, 2002, from http://www.sciencenews.org/20020126/bob10.asp

Kent, J.R., Parent, R.E., & Carlson, W.E. (1991). Establishing Correspondences by Topological Merging: A New Approach to 3-D Shape Transformation. Graphics Interface '91, 271-278.

Kerlow, I.V. (1996). The art of 3-D computer animation and imaging. New York: John Wiley & Sons, Inc.

Lasseter, J. (1987). Principles of traditional animation applied to 3D computer animation. Computer Graphics, 21, 35-44.

Layborne, K. (1998). The animation book. New York: Three Rivers Press.

Lerios, A., Garfinkle, C.D., & Levoy, M. (1995). Feature-based volume metamorphosis. Proceedings of the 22nd annual conference on Computer graphics and interactive techniques, 449-456.

Maestri, G. (1999). Digital character animation 2 (volume 1). Indianapolis, IN: New Riders Publishing.

Magnenat-Thalmann, N. & Thalmann, D. (1997). Computer animation. In A.B. Tucker (Ed.), The computer science and engineering handbook (pp. 1300-1318). Boca Raton, FL: CRC Press. Retrieved online version January 15, 2003, from http://www.miralab.unige.ch/papers/107.pdf

O'Brien, J.F., Zordan, V.B., & Hodgins, J.K. (2000). Combining active and passive simulations for secondary motion. IEEE Computer Graphics and Animation, 20, 86-96.

O'Rourke, M. (1998). Principles of three-dimensional computer animation: Modeling, rendering, and animating with 3D computer graphics (Rev. ed.) New York: Norton.

Parent, R. (2002). Computer animation: Algorithms and techniques. San Francisco, CA: Morgan Kaufmann Publishers.

Ratner, P. (1998). 3-D human modeling and animation. New York: John Wiley & Sons, Inc.

Taylor, R. (1996). The encyclopedia of animation techniques. Philadelphia, PA: Running Press Book Publishers.

Thalmann, D. (1996) Physical, behavioral, and sensor-based animation. Proceedings of Graphicon '96, St. Petersburg Russia, 214-221. Retrieved online version January 15, 2003, from http://ligwww.epfl.ch/~thalmann/papers.dir/Graphicon96.pdf.

Thomas, F, & Johnston, O. (1995). The illusion of life: Disney animation. New York: Hyperion.

Vince, J. (2000). Essential computer animation fast. London: Springer.

Weiss, P. (2002). Calculating cartoons: Physics simulations create convincing illusions in films and games. [on-line] Science News, 161, 56.

Williams, R. (2001). The animator's survival kit. London: Faber.

Zhang, Yongyue. (2001). Image Morphing. Retrieved February 15, 2003, from http://www.fmrib.ox.ac.uk/~yongyue/morphing.html.