WHEN PIGS FLY: A STUDY OF COMPUTER GENERATED PAPER FOLDING

A Thesis

by

ELIZABETH JEANETTE NITSCH

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2008

Major Subject: Visualization Sciences

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Approved by:

Chair of Committee,	Carol LaFayette
Committee Members,	Frederic I. Parke
	Michael Greenwald
Head of Department,	Tim McLaughlin

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ABSTRACT

When Pigs Fly: A Study of Computer Generated Paper Folding. (December 2008)

Elizabeth Jeanette Nitsch, B.E.D., Texas A&M University

Chair of Advisory Committee: Prof. Carol LaFayette

The purpose of this thesis is to develop a system for folding an origami model using computer generated, or virtual, paper. This research is detailed according to both the creative and technical aspects of that process, with particular attention given to formulating a solution for animating the paper in a way that is physically realistic. The project is executed in Autodesk Maya, a 3D computer graphics program, and rendered with mental ray, a production quality rendering software. The final results are illustrated via excerpts from *When Pigs Fly…*, an original 3D short which uses the developed methodology to give life to an origami-based narrative. The techniques employed in this thesis can provide a valuable framework for other artists embarking on similar productions and supply a foundation for more advanced problems related to folding and computer graphics.

Ad Astra Per Alia Porci

ACKNOWLEDGEMENTS

I would like to sincerely thank my committee chair, Professor Carol LaFayette, for her guidance during the course of my research. I don't think I would have finished this project without her encouragement. I would also like to thank my committee members, Dr. Frederic Parke and Dr. Michael Greenwald, for their feedback and support.

Additionally, I would like to thank the faculty and staff of the Visualization Science department for their help throughout my time in the program. They have always made my time in the Viz Lab an enjoyable experience.

Last, but not least, I would like to thank my family and friends. Thanks to my parents, for their love and continuous support, my sisters, Allison and Marianne, for their enthusiasm for my project, and my friends, Alberto Galindo and Shaila Haque, for their advice and encouragement.

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CHAPTER I

INTRODUCTION

In the real world, folding a piece of paper is such a straightforward task that one hardly gives it a second thought. Because of this, it is easy to believe that implementing paper folding in a 3D computer graphics (CG) program such as Maya [1], would be fairly simple task.

I first became interested in the problem of creating CG origami when I attempted to model a paper crane for a class assignment. Naively I thought that, by starting with a plane of "paper" and merely pulling the vertices about, I could create something roughly approximating an origami crane. As my crane quickly morphed into a mess of stretched faces, flipped normals, and intersecting polygons, I realized the difficulty of the task. I resigned myself to modeling the crane via a less physically accurate method, and simply extruded a cube into an origami-like shape (Fig. 1). While the final result was acceptable, I knew that the geometry was not at all like that of its real life counterpart.

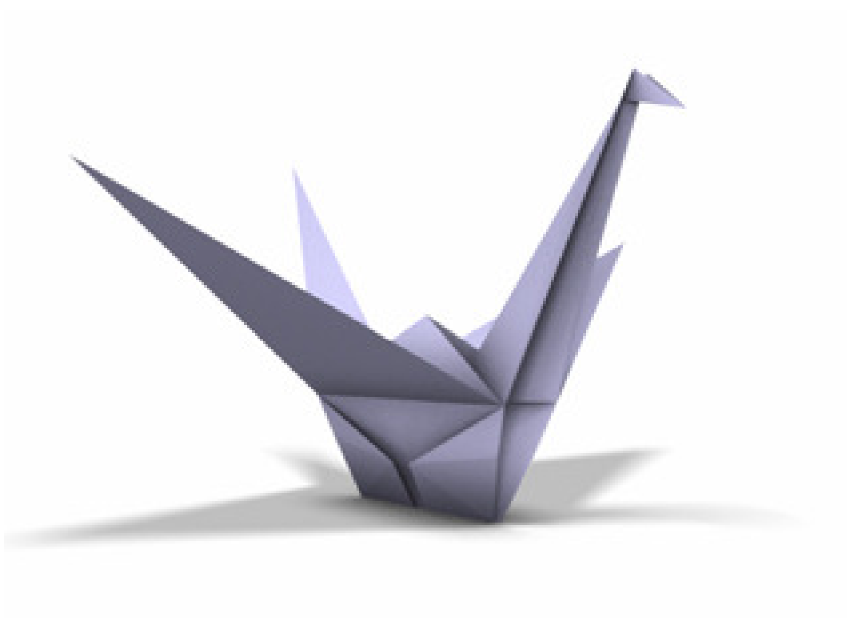

Fig. 1. *Origami Crane* created for VIZA 657, *Computer Aided Sculpting*.

This thesis follows the style of *Leonardo*.

Rather than dismissing the project as impossible, I instead thought of it as something that needed more time and research in order to be executed correctly. Surely Maya, with all of its amazing capabilities, would have a tool or command at its disposal which would allow me to carry out something as mundane as paper folding! However, my own experimentation and the relative paucity of CG animation featuring origami implied that this was definitely not the case. It is surprisingly difficult to create a realistic rendering of even a piece of paper folding in half, and the complexity level only increases with additional folds. Conceptually, it is difficult to understand the intricacies involved in turning a flat, almost 2D, piece of paper into an accurate 3D origami creation (Fig. 2).

Fig. 2. Research.

Maya, it turns out, is poorly equipped to deal with the network of polygons, creases, and intersections which reposition themselves at each step. Creating an origami model in CG, especially one that folds realistically, is therefore a complex challenge with no clear-cut solutions. Instead, it is a problem which requires much finagling, coercion, and attention to detail in order to solve using existing software.

CHAPTER II

BACKGROUND

WHAT IS ORIGAMI?

Origami is the art of taking a piece of paper and, through a series of simple folds, molding it into a chosen, recognizable figure [2] (Fig. 3). Origami has made an impact in the fields of mathematics, geometry, computer graphics, art, and education [3]. It is pursued all over the world by people who are as diverse as their reasons for practicing it.

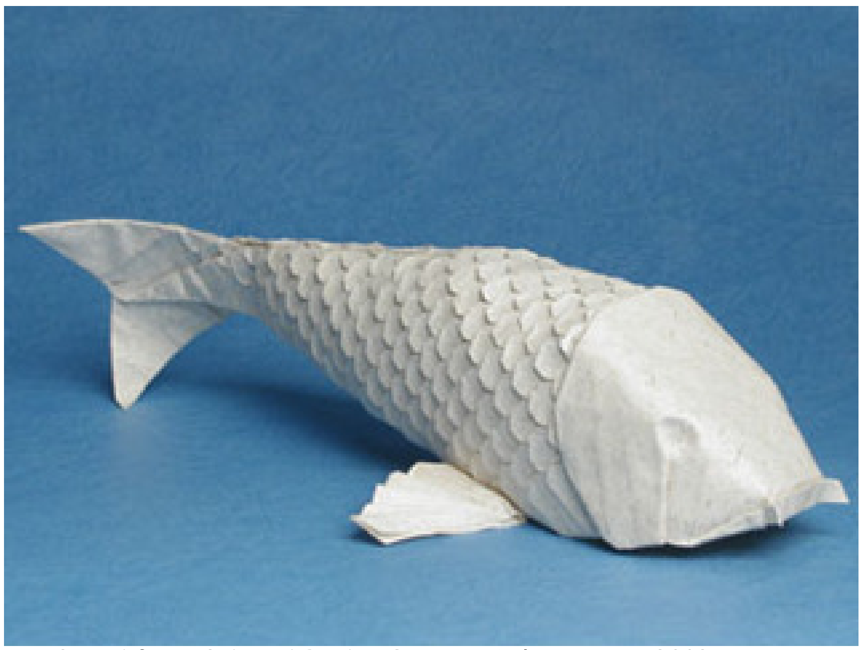

Fig. 3. *Koi* from *Origami Design Secrets*, Robert Lang, 2003.

The basic technique of origami is folding and, while many complex folds have been developed, most origami uses only a small number of simple folds (Fig. 4). It is the combination of these folds that creates varied and intricate designs [4]. Certain arrangements of folds form *bases*, or starting shapes, which are common to the construction of more than one figure. The classic, or best-known bases, are the kite base, fish base, bird base, and frog base [5] (Fig. 5).

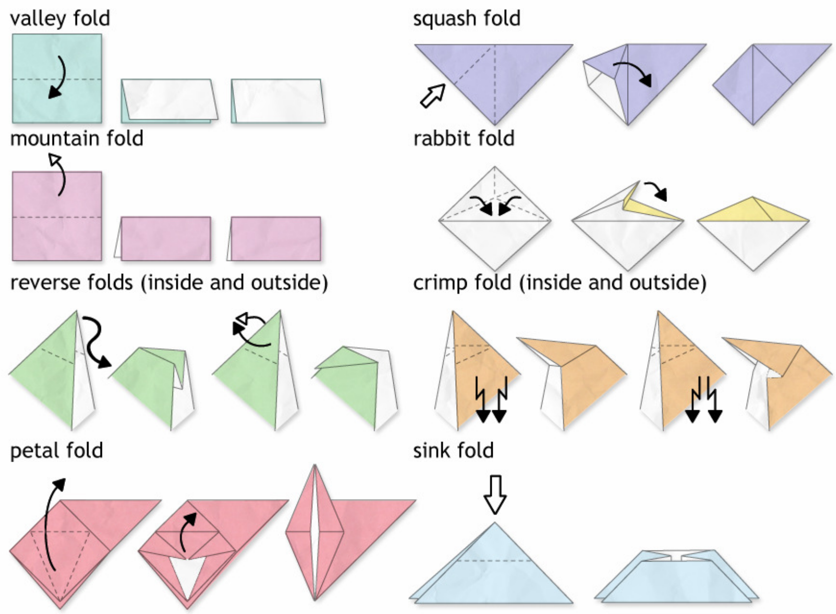

Fig. 4. Basic origami folds, information adapted from *The World of Origami*, Isao Honda, 1965.

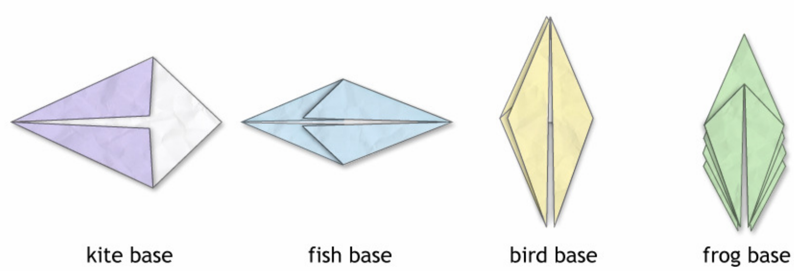

Fig. 5. The "classic" bases, information adapted from *Complete Origami*, Eric Kenneway, 1987.

Finished origami figures are called *models*, and they are created by following one of two methods. Conventional origami diagrams illustrate a linear folding sequence, while crease patterns show all the folds in a single diagram, leaving the paper folder to interpret the correct order [6].

PAPER

Since the only material needed for origami is paper, the art form's development is closely tied to the invention of paper itself. Paper, as we know it today, was first introduced in A.D.

105 by Tsai Lun, an official with the Chinese court. It was first brought to Japan by Dokyo, a Buddhist monk, in A.D. 610. As trade routes opened up between the East and the West, the secret of papermaking spread first to the Middle East, and then later to Europe [7].

Paper is unique because of its paradoxical qualities. It is a temporary material (often crumpled up and thrown away) but at the same time it is a long lasting one (there are books in existence over 1,500 years old). It is usually thought to be delicate, yet can have a strength that makes it impossible to fold [8]. Though typically conceptualized as a flat, two-dimensional object, paper has a physical thickness no matter how thin it may seem. It appears to be a homogeneous material; however it is heterogeneous to such a degree that scientists find it difficult to relate its structure to its physical properties [9].

Paper's diverse nature can be directly attributed to its composition. Paper is a fibrous substance made of cellulose, the chief component of plant cell walls, and a range of fillers. Common sources for the fibers include wood pulp, cotton, hemp, linen, or rice, and the choices for fillers are equally numerous. The manufacturing method also plays a significant role in paper's distinct structure. At each stage in the paper-making process, there is an opportunity to control the weight, density, strength and grain [10]. The ability to create a substance with such endless variety means that there are few limitations to what paper can do, how it can be manipulated, or what it can be used for.

Origami can, and has, been made with paper of all types, but conventionally a thin, square shaped piece of paper (colored on one side and white on the other) is used. In Japan, the traditional paper is called *washi*, a word that means "Japanese handmade paper." This paper, made from the long inner fibers of three plants (*kozo*, *mitsumata*, and *gampi*), is remarkably versatile. It is strong and durable and at the same time light, soft, and translucent. These qualities make the paper suitable for everything from clothing and architecture to lanterns, kites, and, of course, origami [11].

HISTORY OF ORIGAMI

Given that paper originated in China, many historians trace the development of artistic paper folding to that country. At the same time, there is evidence that folding may have been cultivated independently in European countries such as Spain, and Germany. Regardless of its beginning, Japan is the country where paper folding was taken and elevated to an art form. Paper folding was first used there for religious and ceremonial occasions, but over time it developed into a recreational pastime, with people folding simply for enjoyment. The first written instructions on origami appeared in 1797 with the publication of the *Senbazuru Orikata*, a book which describes how to create connecting cranes from one sheet of paper [12] (Fig. 6). The word “origami”, which literally means to fold (*oru*) paper (*kami*) in Japanese, was not coined until 1880. Now, this term is commonly used around the world to describe all types of paper folding, including those of non-Japanese origin [13].

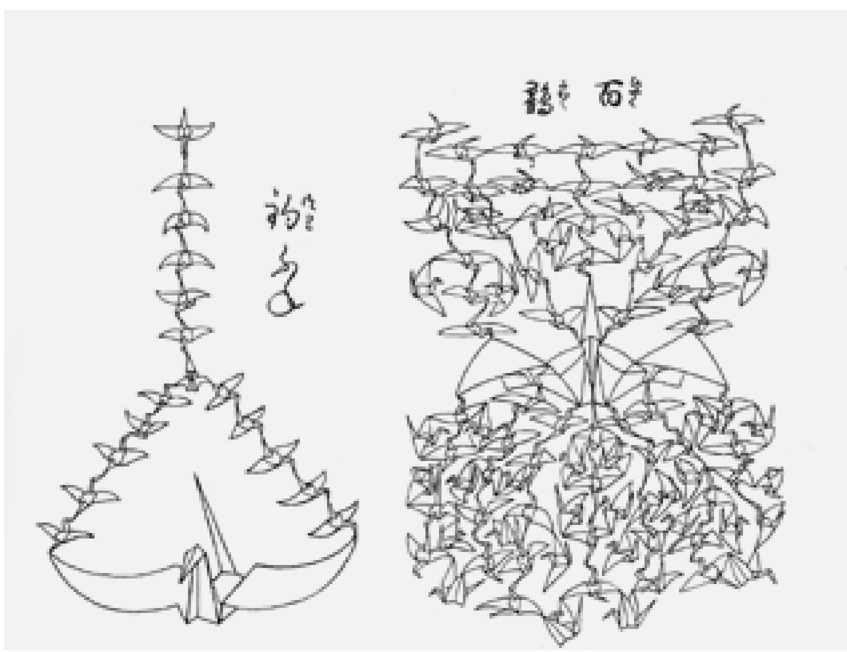

Fig. 6. *Senbazuru Orikata* from *Folding the Universe*, Peter Engel, 1989.

While origami is now a respected art form with enthusiasts of all ages, this was not always the case. Until the 1950s, origami was primarily considered a children's hobby and the designs were mostly very simple. In 1951, Akira Yoshizawa published *Atarashi Origami Geijutsu* with completely new, and surprisingly complex, models [14] (Fig. 7). He pioneered many novel techniques and, together with Sam Randlett, developed a standard set of notation for diagramming origami folds. Yoshizawa's work led to an origami renaissance and elevated paper folding to an art [15]. Since then there have been many innovations in the art form and the complexity and detail of some models today is staggering [16] (Fig. 8).

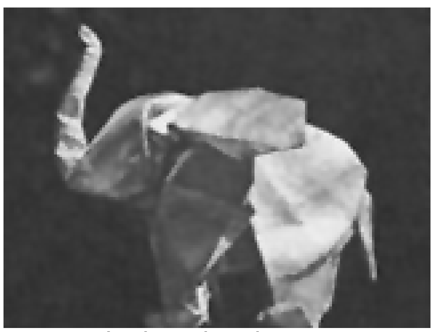

Fig. 7. *Elephant* by Akira Yoshizawa from *The Art of Origami*, Sam Randlett, 1963.

Fig. 8. *Songbird* from *Origami Design Secrets*, Robert Lang, 2003.

ORIGAMI IN MOTION

Even though origami has traditionally been a static art form, it has also been used for the purpose of animation. The first instance of this is the British produced *Snip and Snap* created between 1958 and 1960 [17] (Fig. 9). This children's television show featured cut-and-folded origami animal characters that were crafted and animated by Danish artist Thoki Yenn (working under the pseudonym of Thok Sondergaard). Another early example is the Italian TV series *Quaq Quao* written and directed in 1978 by Francesco Misseri [18] (Fig. 10).

Fig. 9. “Top Dogs” from *Snip and Snap*, Halas & Batchelor Collection, Ltd., 1960.

Fig. 10. *Quaq Quao*, L + H Films, 1978.

Both of these animations were created using the traditional stop-motion approach, the only practice readily available at the time. Stop-motion is the term used to describe an animation technique in which an object, in this case paper, is changed by small amounts between individually photographed frames in order to create the illusion of movement. This process is extremely tedious and can be prone to mistakes and imprecision. It is also limited in its ability to show movement since, by nature, it can only capture key poses and must neglect any in-between actions.

Although other options are available today, many animations still rely on the old frame-by-frame method. The European Parliamentary Elections advertisement, “Origami”, produced by Loose Moose Ltd., is a good example of this. The advertisement opens with a government leaflet falling to the floor and transforming itself into whimsical origami models (a flower, a train, a factory, and a chicken) meant to illustrate various interests of the European Union. Although this commercial is well-executed and entertaining, the origami on screen is not physically accurate. The folds happen in such a few frames that significant steps are skipped over completely and, what's more, some of the models featured could not have been created from the same single piece of paper [19] (Fig. 11). These are all traits that are common to origami animations constructed by means of stop-motion. While these inaccuracies rarely detract from the films’ charm, it does make them poor examples of realistic paper folding.

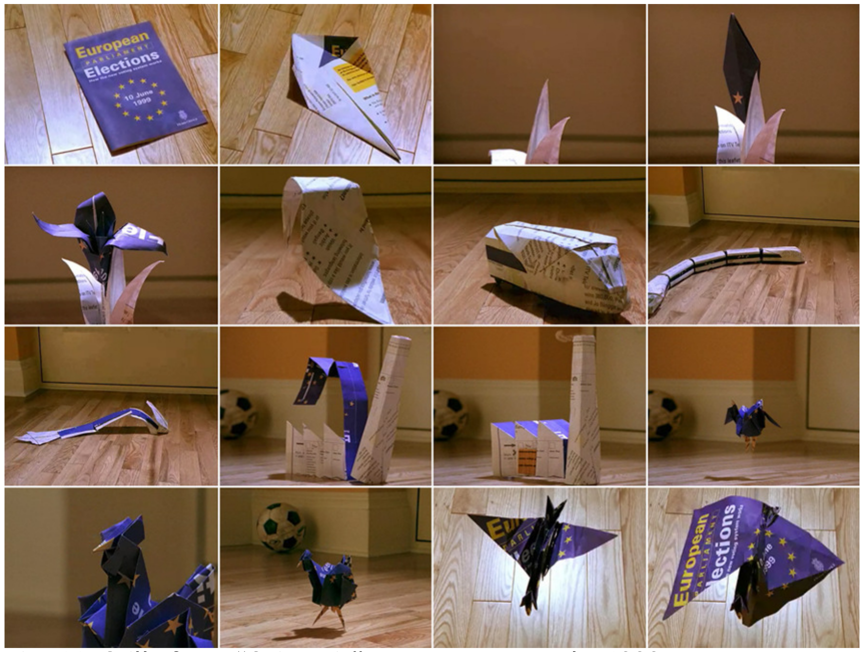

Fig. 11. Stills from “Origami,” Loose Moose, Ltd., 1999.

The basic idea of animating origami has subsequently been revisited using computer graphics. The first major illustration of this is the Citibank commercial, “Bunnies”, produced by Will Vinton Studios [20] (Fig. 12). Although the studio was known for its work in stop-motion animation, Will Vinton decided to go completely CG for this spot featuring origami bunnies made from dollar bills. Their effort was rewarded, and the commercial ended up winning eighth place in Animation Magazine’s “Anicomm Awards.” Since then, origami has proven itself to be an appealing and eye-catching means of attracting attention in television advertisements, as well as in the occasional movie. Two of the popular *Harry Potter* films can boast scenes featuring paper folding [21] [22] (Fig. 13), and origami models also play a small role in Disney’s *Chicken Little* [23] (Fig. 14). Additionally, there have been several more recent commercials where origami figures prominently. The most elaborate of these are Merritt Productions’ commercial for the Mitsubishi Endeavor [24] (Fig. 15) and Version2’s “Introduction for the Fifteenth Annual Association of Independent Commercial Producers (AICP) Show” [25]. The Mitsubishi commercial is unique in that it combines traditionally modeled (real paper) origami sets by Robert Lang and Linda Tomoko Mihara with animated CG origami models. The AICP animation, which shows paper objects flowing seamlessly into different sponsor cards, is notable for being the first of these examples to even endeavor to show the paper in the process of folding.

Fig. 12. “Bunnies,” Will Vinton Studios, 2000.

Fig. 13. *Harry Potter and the Chamber of Secrets*, Warner Bros. Studios, 2002.

Fig. 14. *Chicken Little*, Walt Disney Studios, 2005.

Fig. 15. “Mitsubishi Endeavor SUV,” BBDO, 2006.

One might assume that a CG representation of origami would eliminate some of the physical inaccuracies observed in stop-motion animations. Unfortunately, this does not seem to be the case. If anything, CG origami seems to be more unrealistic than its frame-by-frame counterparts. Nearly all of the above cases shy away from showing the paper actually folding and the lone example that does manages to skip over important steps by presenting this process both very quickly and without regard for geometric accuracy [26] (Fig. 16). The non-folding CG models are often clearly constructed of separate paper instead of a complete sheet and the tendency to feature models that seem to come from the same piece of paper but physically could not is even greater.

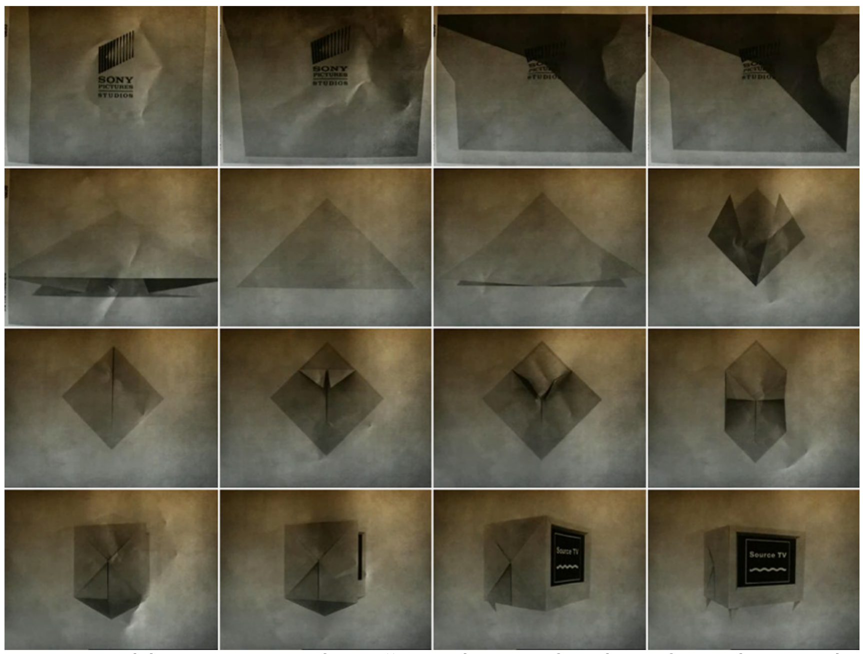

Fig. 16. Folding sequence from “Introduction for the Fifteenth Annual AICP Show,” Version2, 2006.

The reason for these lapses is not entirely clear. It is possible that, in the examples above, these qualities were not desired. It may be that such attention to detail was deemed excessive, since, admittedly, it is hard to discern inaccuracies at 30 frames per second. Nonetheless, the sheer lack of any known examples points to the inherent challenge of the task and probable difficulties with the existing technology. These are problems that my thesis, which is concerned with creating an animation that is more physically accurate, successfully addresses.

CHAPTER III

METHODOLOGY

The goal of this thesis is to develop and implement a technique for animating paper folding in a 3D computer graphics program. This means taking the computer modeled “paper” through all of the steps of the origami model-making process; from a simple, flat plane to the final, complex grouping of surfaces that are meant to represent an identifiable figure.

Maya was selected as the primary instrument for this task since its features are representative of most commercially available CG software. It is also the de-facto industry standard, being widely used in both the film and television industries.

An origami model, in this case a bunny, was chosen as an example for working out the basic folding procedure. Its folding instructions, shown as a linear diagram, are the framework that the animation should conform to [27] (Fig. 17). Although the directions that follow are specifically detailed with regards to the creation of an origami bunny, the general methodology is adaptable to many other origami models.

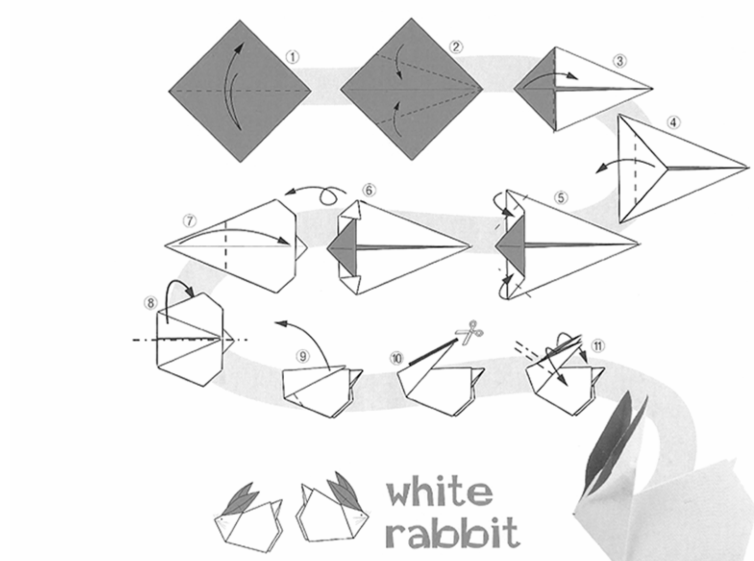

Fig. 17. *White Rabbit* from *Origami: Page-A-Day Calendar*, Margaret Van Sicklen, 2007.

MODELING

Before any folding can take place, it is important to decide how to represent a piece of paper in the computer. Maya supports three popular modeling options, NURBS, subdivision surfaces, and polygons. Because NURBS and subdivisions are best suited for more freeform surfaces, polygons are the superior and more logical choice for modeling a sheet of paper.

To create a CG representation for a piece of paper some very basic modeling techniques are utilized. *Create* > *Polygon Primitives* > *Plane* produces a simple plane, or flat surface, that is centered at the origin. The width and height options should be adjusted to correspond to those of a real life equivalent (in this case, 4 inches by 4 inches) and there should be no subdivisions of the plane (Fig. 18).

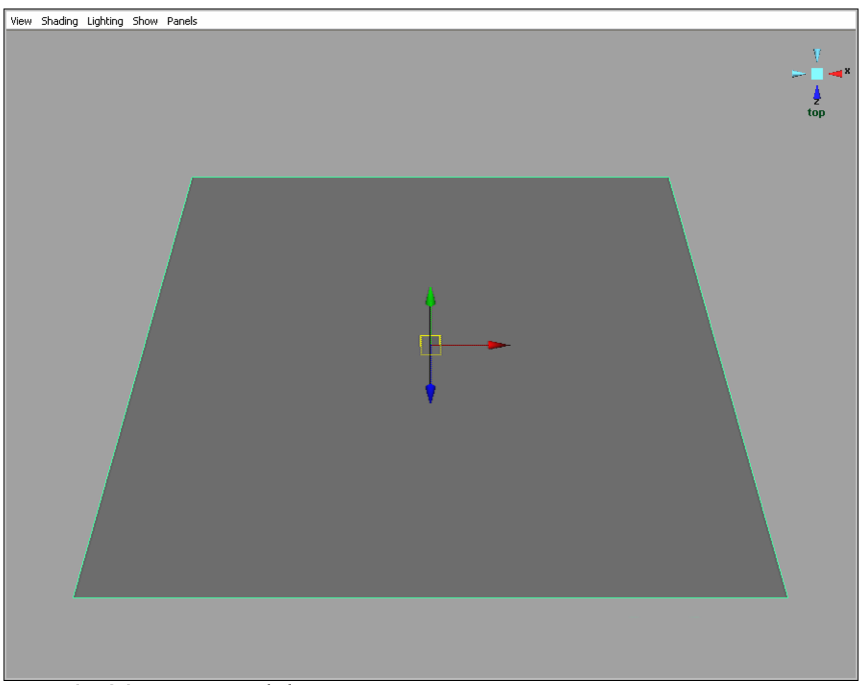

Fig. 18. CG paper model.

Like all tangible objects that exist in the real world, paper is a 3D material. Yet, because it characteristically has a very minute thickness, it is sometimes thought of as being planar. If this thesis were striving for absolute physical accuracy, then it would be necessary to slightly extrude the existing plane in order to create a paper model that depicted this. Such precision would unfortunately go to waste since not only is it nearly imperceptible to the naked eye, but this doubling of geometry only adds to the difficulty of actually folding the paper (Fig. 19). Therefore, for these purposes, paper will be represented as a flat plane, with no physical thickness. Modeling it in this way is both simpler and more efficient.

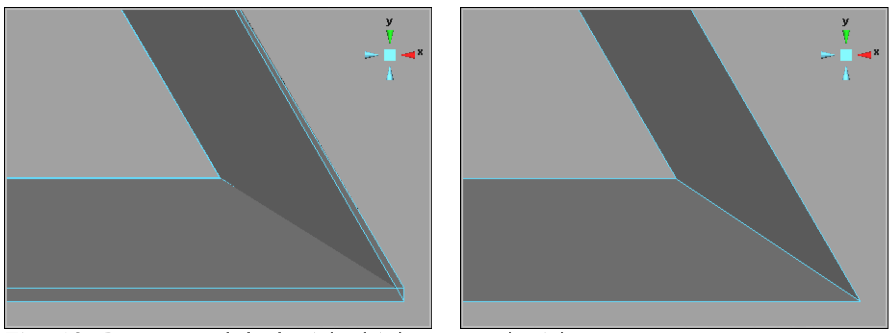

Fig. 19. Paper modeled with thickness and without.

A square piece of paper starts out as essentially a single face, four vertices linked by four edges. As it is folded, however, this single plane is partitioned up into many planes. Each fold represents a new division which means another crease, or edge, and additional vertices. In order to be able to fold the paper later on, in the rigging and animation stage, it is necessary for all of this geometry to be present from the very beginning. The placement of this geometry can be derived by looking at the crease pattern of the origami model.

Crease patterns are a relatively new development in the field of origami, having only become popular in the past ten to fifteen years. They condense all of the folds, and for complex models that can mean hundreds, into a single diagram and leave the step-by-step instructions to be worked out, or deduced, by the user. Unbelievably, most crease patterns are constructed before the figure is even folded, as part of the process the model maker goes through in order to map out and polish the design [28]. However, in this case, the crease pattern will be determined after folding a real world model from the linear diagram and then carefully unfolding it to see where the creases occur (Fig. 20). Next, simple geometry is employed to determine the exact location of each vertex (Fig. 21).

Fig. 20. Crease pattern, derived from folding.

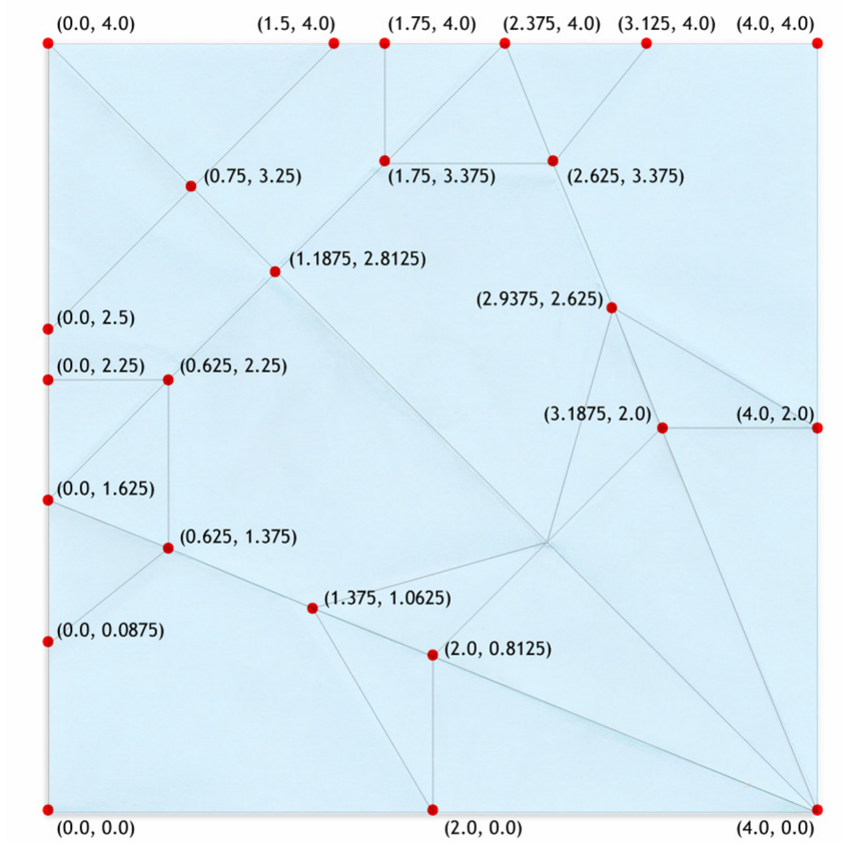

Fig. 21. Crease pattern geometry.

This information is then used to split up the paper plane of the CG model. It is important that vertex placement be as accurate as possible. To facilitate this, it is beneficial to use *locators*, Maya's dummy objects for marking a particular position in world space. Locators are placed precisely where each vertex must go and then used as guides for dividing up the plane (Fig. 22). With *Snap to Points* turned on, the *Split Polygon Tool* (*Edit Polygons* > *Split Polygons*) is used to latch onto each locator in turn and draw boundaries across the existing paper plane. In this way, the correct folding pattern can be built into the model (Fig. 23).

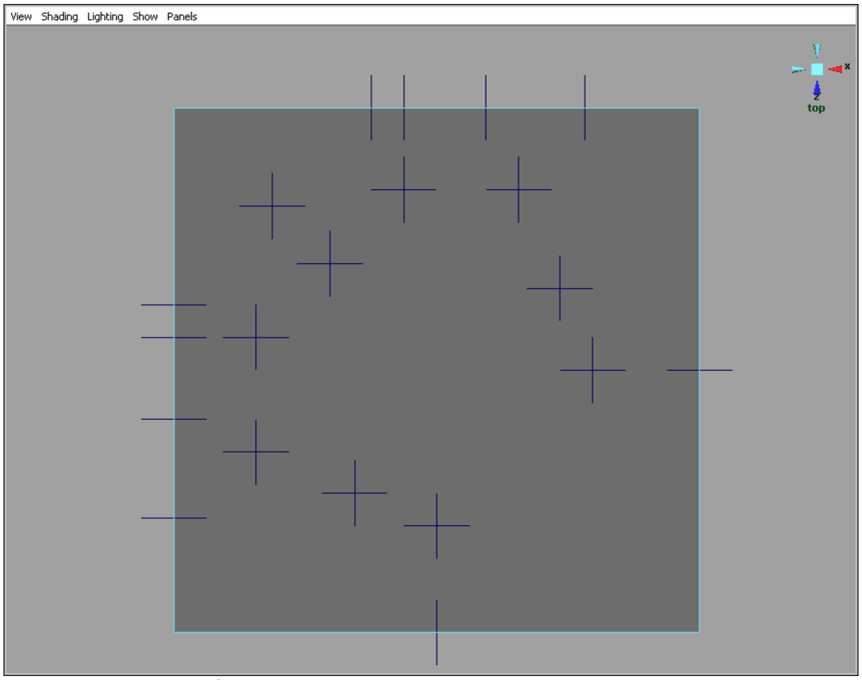

Fig. 22. Locator placement.

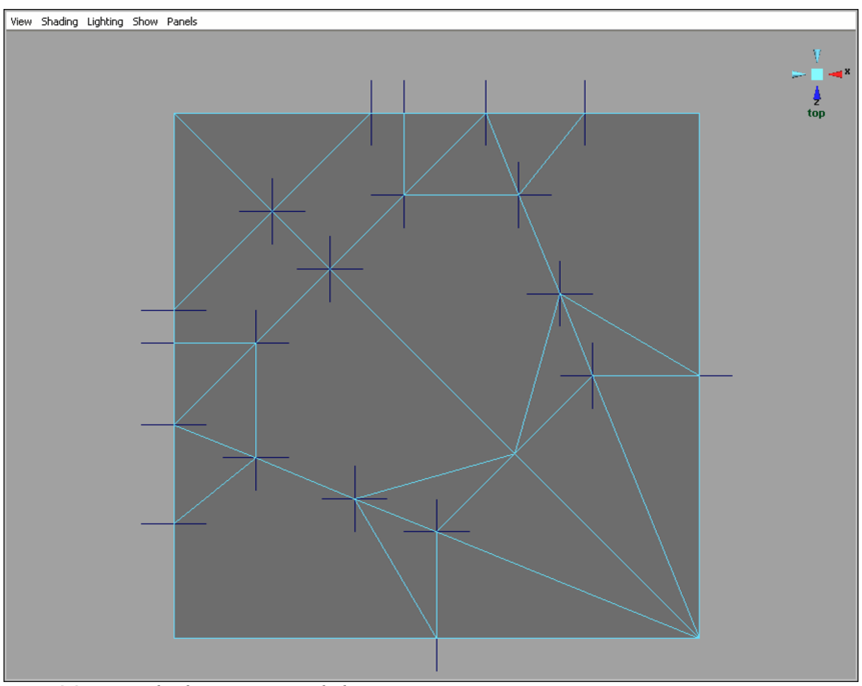

Fig. 23. Divided paper model.

After all the creases are inserted the next step is to unwrap, or arrange, the model's UV coordinates in preparation for texture mapping. UVs are points that correspond to polygonal vertices and UV unwrapping is the process of arranging those points to create a 2D image that is representative of the overall 3D model. A clean and accurate UV map can be generated by simply selecting the plane in the top camera view and applying *Polygon UVs* > *Planar Mapping* > *Mapping Direction: Camera*. *Planar Mapping* projects UVs onto a mesh through a plane. Since a piece of paper is both completely flat and completely visible from one camera angle, this is the most appropriate unwrapping choice. The UV map can be viewed using *Window* > *UV Texture Editor*. If unwrapped correctly, it should precisely match the crease pattern of the original origami model (Fig. 24).

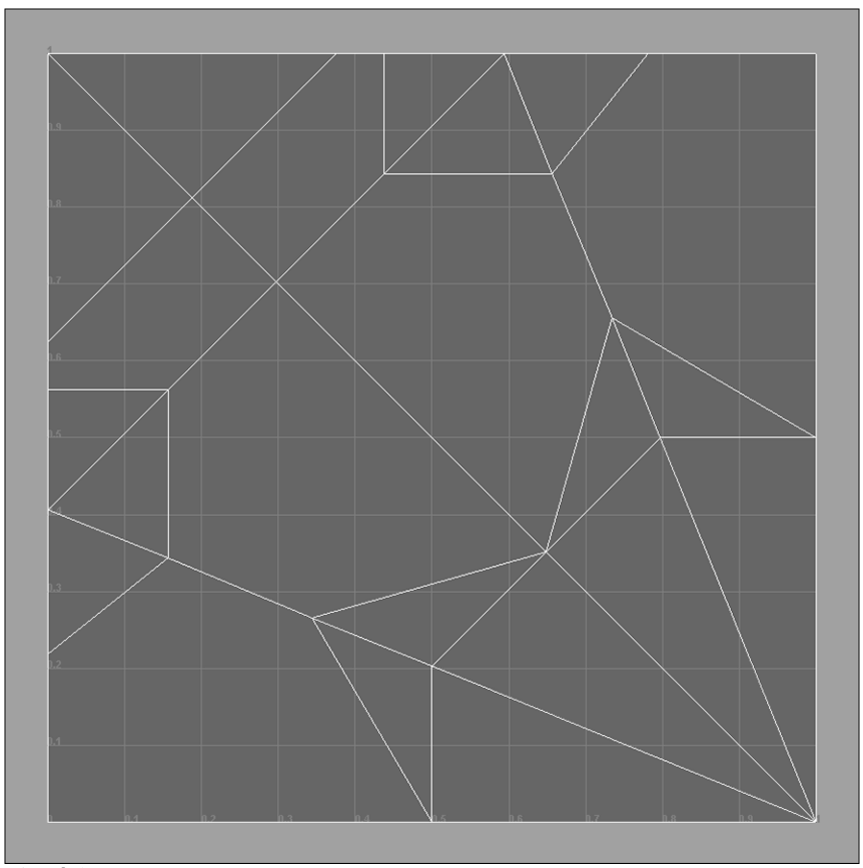

Fig. 24. UV map.

RIGGING AND ANIMATION

Bringing the origami paper to life requires *rigging* of the paper model. In computer graphics, the term rigging typically refers to the process of preparing a 3D mesh for animation via a skeletal system of joints and bones [29]. However, here the word is employed more loosely to denote any mechanism that is used to articulate the model.

Because there was no previously established means of rigging origami in Maya, the techniques used to animate the folding process were largely arrived at through trial and error. Although Maya offers many options for animation, most of these are not conducive to depicting either the unique qualities of paper or the distinctive motion of paper folding. Of those methods that did show potential, three (skeletal animation, clusters, and blend shapes) were ultimately selected for further examination. Each was applied to the CG model in an attempt to animate the folding of an origami bunny. The following sections offer a detailed appraisal of the advantages and disadvantages of each technique along with documentation of the final solution.

Skeletal Animation

The more conventional method of rigging, *skeletal animation*, was the first of these to be tested. Skeletal animation relies on a system of *joints* and *bones* to drive the animation of a mesh. Joints and bones are the building blocks of the skeleton. When several joints are placed together on screen, they are connected linearly, with bones forming the paths in-between. These components create a hierarchical network, with the higher-up, or *parent*, joints affecting the *child* joints below. Once the skeleton is built, it is bound, or *skinned*, to the polygonal mesh. Skinning associates each bone with a corresponding group of vertices so that when the joints are rotated, or otherwise transformed, the model will be deformed as well [30].

Skeletal animation is a logical solution because, apart from being a classic rigging mechanism, the motion of the joints is perfectly suited to the folding of paper. Although joints can be translated and scaled, they are primarily used for rotation about an axis. In the same way, most origami folds can be described as rotations. When a piece of paper carries out a mountain or valley fold, it is revolving 180 degrees around a crease line. Likewise, when a reverse or crimp fold is executed the paper is simply rotating away from a given point.

Joints are created by means of the *Joint Tool* (*Skeleton* > *Joint Tool*) and their effectiveness can be tested only after binding the paper model to the skeleton (*Skin* > *Bind Skin*). Maya offers two options for skinning, *Rigid Bind* and *Smooth Bind*. The major distinction between the two is related to how the weight, or influence, exerted on each point is divided up between joints. With rigid binding, only one joint can influence a particular vertex. Conversely, smooth binding allows multiple joints to wield a percentage of influence over the same point. Rigid binding is more appropriate in this situation because the movement of the paper is hinge-like rather than smooth or organic.

To begin rigging a piece of paper, it is necessary to first establish a functional arrangement for all the joints and bones. This can be done by observing the crease pattern diagram and the step-by step instructions to determine exactly which components are rotating and where that movement is rooted. Upon examination of the bunny diagram, the first step appears to be fairly straightforward. The placement of a *root* joint at the center with bones extending outward is all that is needed to fold the paper in half. The bones for the second step also need to lie along this axis, so their joints must be incorporated as well. However, it is important to note that the diagonal placement of these folds makes it necessary to reorient the local rotation axes for each. Because the third and fourth steps are similarly undemanding, at this point the skeleton seems to be coming together (Fig. 25).

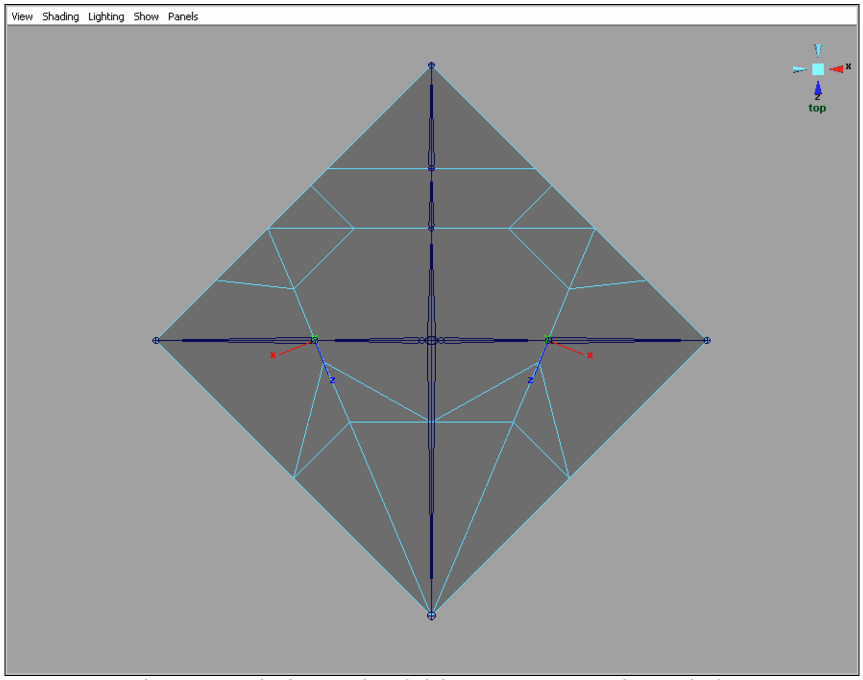

Fig. 25. Preliminary skeleton for folding steps one through four.

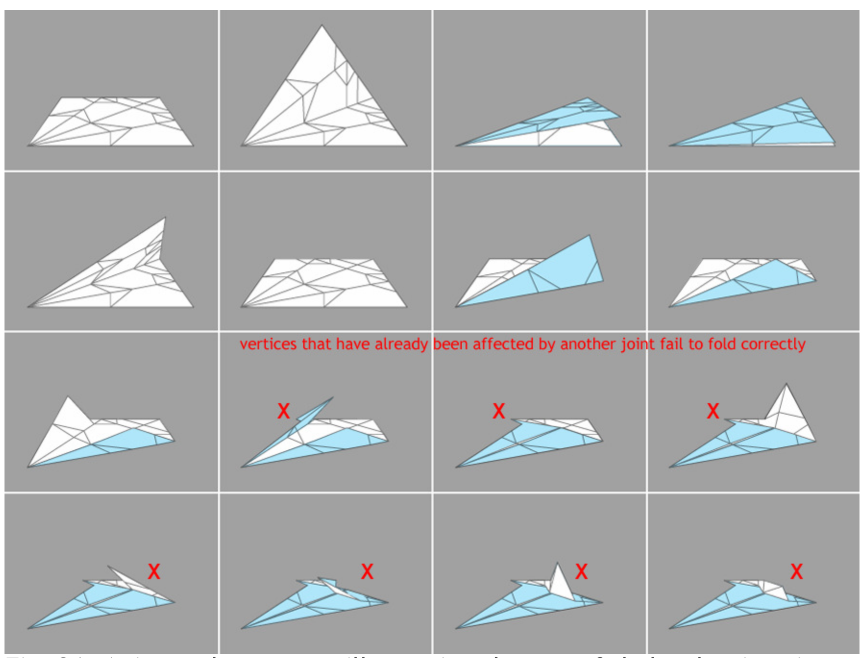

Fig. 26. Animated sequence illustrating the use of skeletal animation for paper folding.

Unfortunately, once the rig is bound to the model this is no longer the case. When the joints are rotated to simulate the folding process, the paper does not fold as planned (Fig. 26). This is because rigid binding allows only one joint to effect each vertex. To fold the paper in half, many of the vertices were already assigned, making them unavailable for later steps. Since this fold is merely needed to demarcate the center of the paper, it would be easy to skip over it and revise the rig accordingly. This same problem would then be encountered at the fifth step and, if those folds were to be somehow eliminated, again at the seventh. Because of this, it is impossible to successfully complete the origami model.

Clearly, skeletal animation has some serious limitations. The manner in which rigid binding assigns weights to each vertex makes it a challenge to work through all of the steps. As the folding process progresses, portions of the model that have previously been assigned to specific joints need to be folded again. Since there is no way to rearrange the vertex weighting midway through, it is not possible to make this method work with a single mesh.

It can also be difficult to arrange the system of joints and bones. Mountain and valley fold, like the ones in this example, are the simplest to map out since it is fairly evident where their pivot points should be. Diagonally oriented folds are a bit trickier since their pivot points are, by default, incorrect. Their local rotation axes need to be manually reoriented. Others, such as the petal and squash folds, may not even be possible with joints due to their multidirectional rotations. No matter what type of folding, an origami diagram requires skeleton building becomes more complicated the farther along one is in the instructions. As the model begins to take shape, its structure changes drastically from a flat plane to a recognizable figure. Since the skeleton is laid out when the paper is still in its initial form, visualizing joint placement for the latter folds is particularly challenging.

Besides these complications, there is the additional difficulty caused by intersection amongst the various planes. When a piece of paper is folded in the real world, it is easy to think of it as folding perfectly flat, with one side laying atop the other. However, if one attempts to replicate this arrangement in Maya, the two portions will literally exist in the same area of space. This overlap makes it difficult for the renderer to know which section is really on top. To contend with this, it is necessary to rotate each joint slightly less than 180 degrees, thus keeping the two sides from intersecting (Fig. 27). While this fix will be satisfactory in the short term, as several folds build on top of each other it will become difficult to avoid intersections by simple altering the rotation. When this occurs, additional rigging mechanisms (such as clusters) may need to be used to move the intersecting planes away from each other. With so much geometry trying to exist in a tight space, intersection is a significant concern regardless of the rigging mechanism employed.

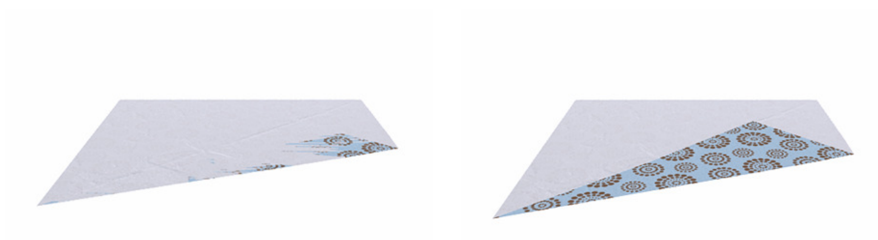

Fig. 27. Paper with intersection and without.

Blend Shapes

Two types of *deformers* showed promise as well. Deformers are sophisticated tools for manipulating the basic control points (NURBS CVs, lattice points, or polygonal vertices) of CG geometry [31]. The first of these to be examined was the *blend shape*. A blend shape is a Maya deformer that changes or morphs an object from one form into another. Blend shapes are produced by creating duplicate versions of the original mesh, rearranging their geometries (without adding or subtracting any vertices), and referencing them within the initial model through the use of a blend shape deformer [32]. The result is a lone mesh that is able to transition from pose to pose.

Blend shapes appear to be ideally suited to the animation of CG paper because of their ability to unite many forms within a single mesh. Looking at the linear diagram, it is possible to imagine each fold being represented by a different model. In the end, the various poses the paper assumes are really just unique combinations of the same polygons, edges, and vertices. No matter how complex or elaborate the final origami creation appears, the fundamental dimensions of the paper remain the same throughout the folding process.

Before applying any blend shapes, it is necessary to become familiar with the terminology that describes them. The original model, in this case the flattened paper, is called the *base shape*, and the posed models are referred to as *target shapes*. To use blend deformers for origami animation, the initial step is to duplicate the base shape. The new model is then adjusted to reflect the paper's position following the completion of the first fold. This transformation can be accomplished in one of two ways. When the required fold is relatively straightforward, the essential vertices can simply be selected and pulled over to their new positions. For more precision, or harder to visualize folds, another rigging mechanism (such as a clusters or joints) can be used to produce the target shapes.

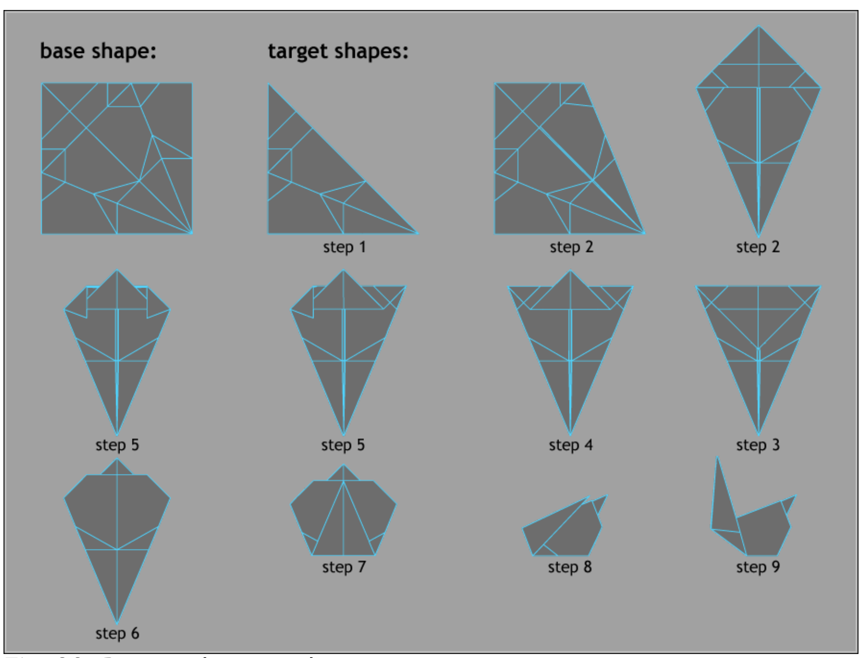

Fig. 28. Base and target shapes.

After the new model has been formed, it is copied and modified according to the next step in the diagrammed instructions. This procedure is repeated until a target shape has been created to correspond with every step in the folding process (Fig. 28). At that point, the first target shape and the base shape are selected and the blend deformer is applied (*Deform > Create Blend Shape*). The other models are then selected in turn and added (in the same manner) to the base mesh. The blend shape deformer creates a keyable attribute, managed through the blend shape editor (*Rendering > Animation Editors > Blend Shape*), which facilitates the transformation of the base model from target shape to target shape. By keying the individual blend shapes in order (from flat plane to final origami figure) an animation can be produced.

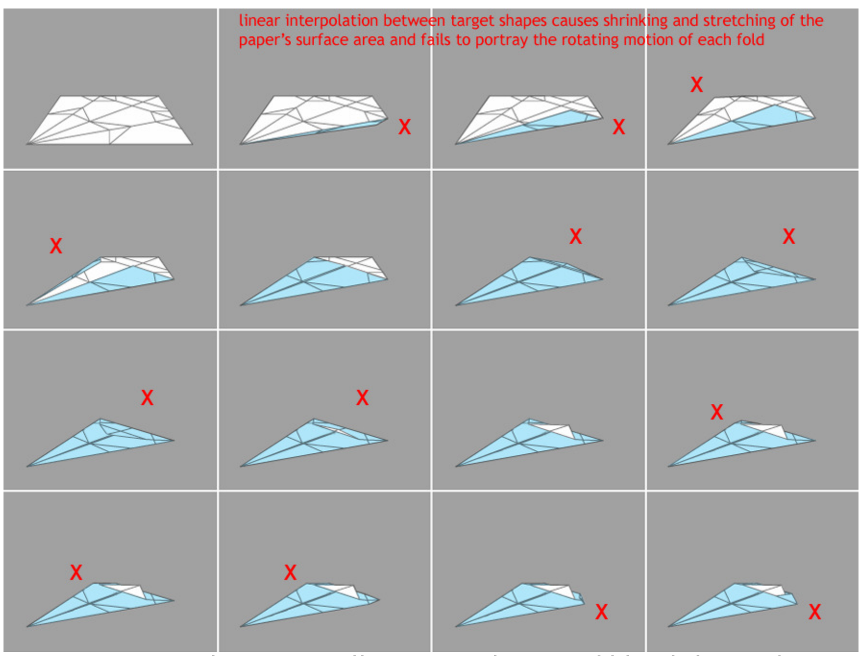

Fig. 29. Animated sequence illustrating the use of blend shapes for paper folding.

Looking through the frames of the animation it becomes evident that, in spite of their initial promise, blend shapes are not a viable solution for this project (Fig. 29). When a vertex changes position, the blend deformer interpolates the movement linearly, taking the shortest path between the two locations. This produces dramatic stretching or shrinking of the paper's overall surface area and, in some instances, results in unrealistic intersections as the translating vertices cut through other parts of the model. It also makes it nearly impossible to replicate the rotating motion that is essential to realistic paper folding. Although this last problem could be somewhat alleviated through the use of intermediary shapes, blend deformers would still be a poor option since, for certain folds, an additional model would be required for almost every frame in the animation.

Clusters

Clusters were the other deformer to be assessed. A cluster is a type of deformer which allows control over a group of weighted points. When applied to a selection of vertices on a polygonal mesh, the cluster deformer creates a new set whose membership consists solely of those points. This set is visually represented by a cluster deformer handle or “C” icon. The weight, or influence, that the cluster handle exerts can be edited for each individual point. As the handle is transformed (by translation, rotation, or scaling) the vertices move based on their specified weights [33].

Clusters are most frequently used to deform facial models in order to simulate various expressions. However, they also show potential as a technique for realizing CG paper folding. Unlike blend shapes, clusters allow for rotation about an axis. As a result, accurate interpolation between poses is feasible. Clusters are also added directly to the mesh, making them easier to set up then the sometimes cumbersome joint chains.

To utilize clusters for paper folding, it is important to begin by examining the linear diagram and establish precisely which vertices are being repositioned at each step. Then, starting with the first fold, the appropriate vertices are selected and a cluster deformer is created to represent them (*Deform* > *Create Cluster*). When the cluster is initially added, the handle, which also acts as the pivot point, will be located at the midpoint for that particular set of vertices. Since the axis of rotation for a fold is actually the crease line itself, this default placement is incorrect and must be adjusted in order to reflect the true position. After the handle has been moved, the cluster is keyed to show the paper in its initial pose and then, several frames later, its pose once the fold has been completed. When keying the cluster attributes it is important to only change those associated with rotation since even minor transformations of the other values (translation and scale) will warp the structure of the paper model by shrinking or stretching it (Fig. 30).

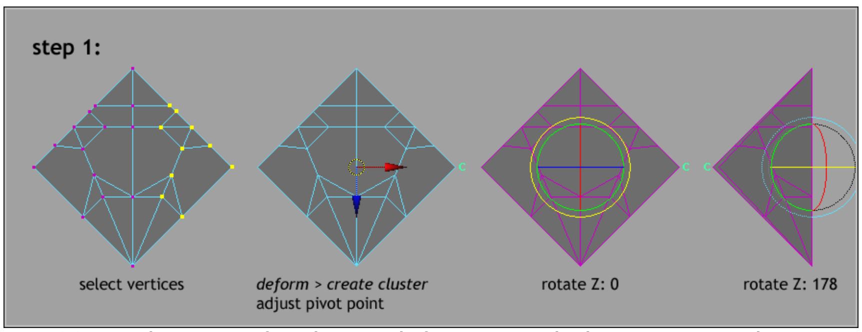

Fig. 30. Application of a cluster deformer, including set-up and animation.

While executing the first (and even second or third) fold in this manner is simple enough, attempting to take the model completely through the folding process is exceedingly difficult. Unfortunately, cluster deformers, like joints and blend shapes, have several limitations which prevent them from being the perfect solution for this project. It is simply not possible to apply all the required clusters to a single mesh without experiencing undesirable and problematic deformation effects. These arise when a vertex belongs to more than one cluster set and is subjected to multiple transformations from the different deformers. The transformations pile up on one another, resulting in incorrect and often extreme shape changes (Fig. 31).

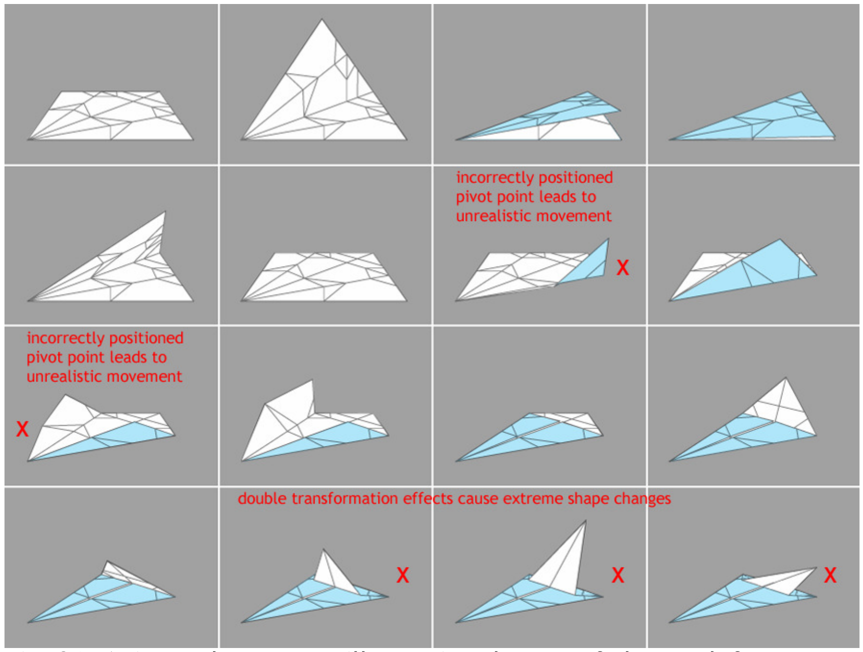

Fig. 31. Animated sequence illustrating the use of cluster deformers for paper folding.

An additional problem concerns the ability of cluster deformers to perform all of the necessary folds. Although clusters are better than joints at replicating tricky, non-mountain or valley folds, there are still some motions with which this type of deformer has trouble. The most common problem appears with folds that are diagonally oriented. In this situation the pivot point is incorrectly positioned, making it a challenge to rotate the cluster in a realistic manner. Although Maya allows the user to alter the location of the cluster handle in space, it does not provide a means of reorienting it. This makes it tough to achieve certain folds as there is no way to correctly align the axis of rotation.

Solution

After studying the preceding examples, one might be forced to assume that Maya is incapable of producing an accurate simulation of paper folding. While it is certainly true that none of the examined techniques are wholly suited to the creation of CG origami, outright rejection of the existing software is premature. Although every rigging mechanism exhibited significant deficiencies, each also offered up potential solutions.

It appears that the biggest obstacle to CG paper folding is Maya's inability to support multiple, extreme transformations within a single mesh. Unfortunately, because the software was developed with a much different purpose in mind, the rigging mechanisms provided were not designed for successfully combining such a wide range of poses. However, having seen that some folds are possible on an individual basis leads one to conclude that positive results could be achieved by breaking up the process. Specifically, this translates to a different model and a different rigging mechanism for every step. Although separate models and rigs are not a conventional or even ideal animating practice, it is the obvious way to eliminate any troublesome deformation effects. This will also allow for the best rigging device (be it joints and bones, clusters, or blend shapes) to be selected for each fold.

When applying this solution towards the creation of an origami bunny, each step must be assessed so that the appropriate rigging mechanism is chosen. For the first fold, joints and bones were the most suitable selection. Once drawn, they were bound to the paper model. Next, the joint's rotation attribute was keyed to show the paper being folded. The model was then duplicated in its post-folding state and the same process was repeated for the ensuing steps. Although joints were employed in the first step, cluster deformers were the most prevalent rigging device due to their relative ease of use. Skeletal animation was needed only for the diagonally oriented folds (steps one, two, and five) which would have been impossible to execute with clusters. Blend shapes were also used sparingly, and then only in situations where the shrinking and stretching that they tend to cause would not be noticeable (steps eight and ten). The following image details the models and their corresponding rigging mechanisms (Fig. 32).

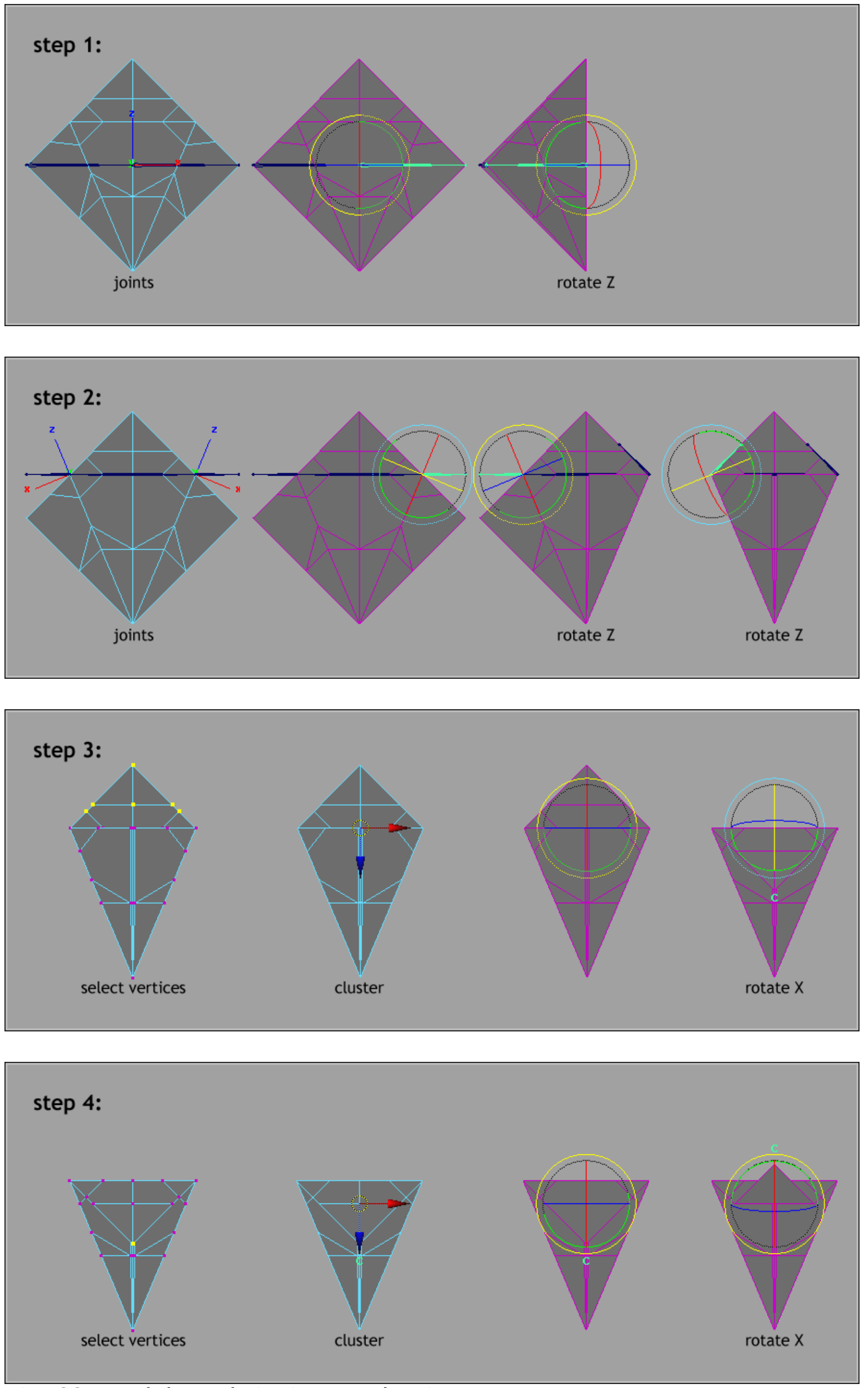

Fig. 32. Models and rigging mechanisms.

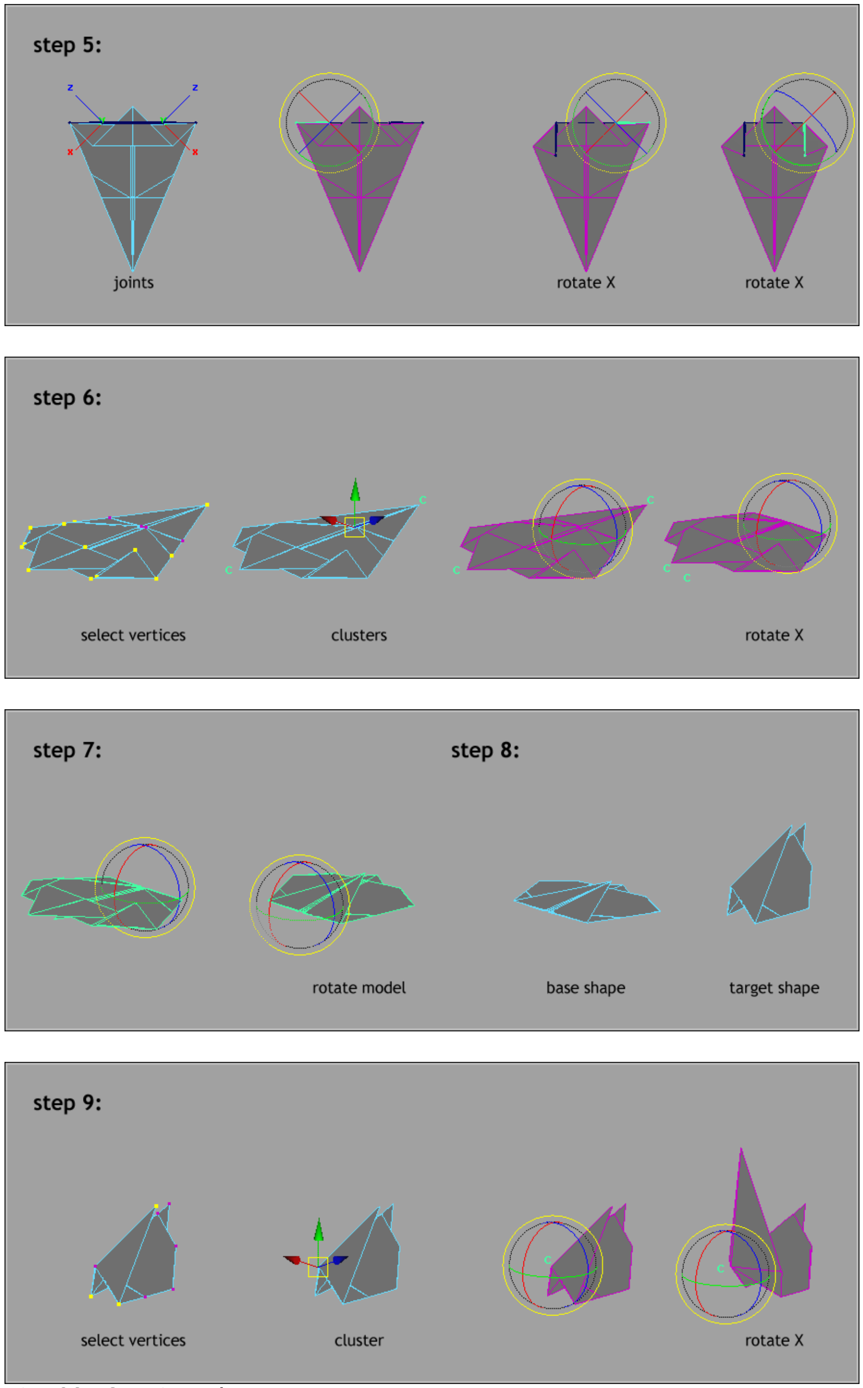

Fig. 32. Continued.

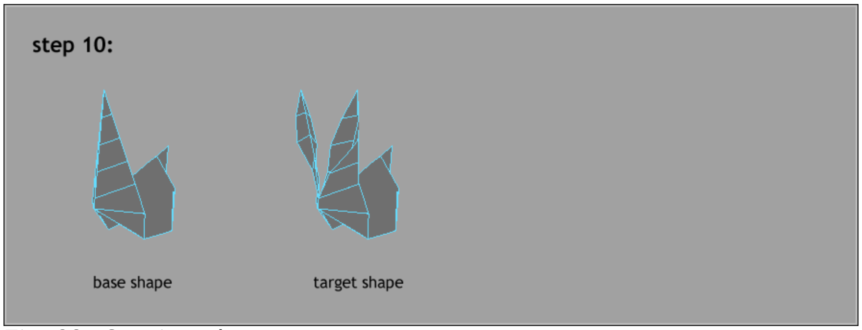

Fig. 32. Continued.

It is important to note here some minor alterations that were made to deal with specific elements of the origami bunny design. At step ten, the instructions called for the model to be cut along the top edge in order to form two distinct bunny ears. To accomplish this in CG, the *Split Vertex* tool (*Edit Polygons* > *Split Vertex*) was used to divide the topmost vertex in two. The newly separated vertices were then pulled apart using cluster deformers. Additional geometry was also added to the ears at this point in order to enhance their shape and dimensionality.

Once these elements were in place, all of the pieces needed to be put together to form a coherent animation. Because so many different models were required to illustrate the folding process, special care had to be taken to create a seamless transition from one model to the next. The best way to do this was to key the *visibility* attribute of every model so that each mesh only appeared onscreen when needed. Visibility is a Boolean attribute that determines whether an object is “on” or “off”, seen or invisible. When the value is set to “0” the object is concealed and when set to “1” it is shown. Unlike other Maya attributes, there is no interpolation between these two values. This means that the object is either completely visible or completely hidden. By swapping the geometry out over the course of a single frame, it was possible to give the impression that a single piece of paper was carrying out all of the folds in the animation.

SHADING

The final step in producing a credible animation is to apply a convincing surface material to the model. In this case, that means a shader which gives a believable imitation of paper. Origami paper has several distinctive visual attributes. It is thin and delicate, with a subtle translucency and two-toned, or duo, coloration. When laid flat its surface is matte-like, but once folded the edges catch the light just enough to reveal a slight sheen. Although paper is surprisingly durable the folding process introduces creases, wrinkles, and other imperfections. All of these qualities make it necessary to use something beyond the default Maya shaders, and indeed, the Maya renderer, in order to achieve a semblance of realism.

mental ray [34] offers numerous advantages over the Maya Software renderer. As a fully integrated plug-in, mental ray provides photorealistic rendering features that are not part of the built-in renderer. These include caustics, physically correct global illumination, and, most significant for this thesis, the ability to support sub-surface scattering (SSS) through a library of custom shaders. SSS is a term that describes what occurs when a light ray pierces the surface of a translucent object and is scattered before exiting at a different point. This is most often visualized in real life by holding a flashlight behind one's hand and observing the reddish glow. It is also seen, to more subtle effect, in a material such as origami paper [35].

mental ray offers three pre-packaged shading networks, known as phenomena, which are equipped to deal with SSS. Of these, the *misss_fast_simple_maya* shader is the best solution for this project. This shader is calibrated to render efficiently and without artifacts. Most importantly, it produces a pleasing simulation of SSS through the use of a baked texture known as a lightmap. An added benefit of this shader is its ability to accept additional node connections in order to form a much more complicated shading network. Almost all of the *misss_fast_simple_maya* shader's attributes are mappable, making it highly customizable. This is important, because the shader "as is" will not provide a passable representation of paper [36].

Typically, when a shader is applied to a model, the entire model takes on the characteristics of that shader. However, in order to accurately represent origami paper's two-toned appearance, it would be, in effect, necessary to assign two shaders to the same surface. While actually doing this is not possible, Maya does provide a means of achieving the same results. Double-sided shading allows a surface to be shaded with a different material on each side. This is done by using a *Sampler Info* utility in conjunction with a *Condition* utility. The *Sampler Info* utility provides many attributes for calculating surface information. In this situation, the *Flipped Normal* attribute is used to indicate the direction of the surface normal and thus determine which side of the surface is being shaded. Because normals, which are used to indicate the orientation of polygonal faces, may only point in one direction, the presence or absence of a normal can be used to differentiate between the colored (Fig. 33) and white sides (Fig. 34) of the paper. The *Condition* utility, which is in essence a Boolean operation, is then employed to specify which texture is mapped to each side [37]. The entire network can be connected to the *misss_fast_simple_maya* material node via the *diffuse_color* attribute, with the result being duo paper that still maintains the distinctive, soft translucency of the SSS shader.

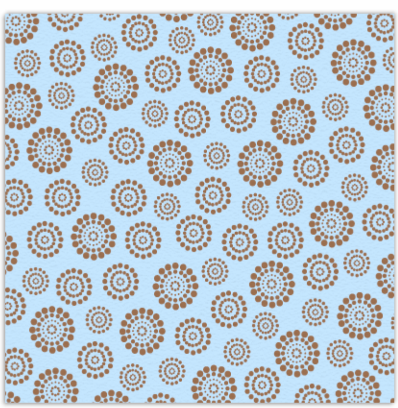

Fig. 33. Colored paper texture map.

Fig. 34. White paper texture map.

Other nodes can be attached to the *misss_fast_simple_maya* shader as needed. In this case, additional connections are required in order to suggest wrinkles and control the shininess of the paper. The folding process produces rumples and indentations as the paper is being creased. Incorporating these into the model would be an arduous task; therefore it is more effective to simulate such imperfections with a bump map. Bump maps are grayscale textures which are used to create the simulation of surface relief. Unlike displacement maps, bump maps do not alter the geometry of the surface. Instead they change the direction of the surface's normals in order to create the impression of depth. A bump map for this project can be efficiently created by first folding, and then unfolding, the model according to a linear diagram. After scanning or photographing the paper the resulting image is brought into a program such as Photoshop [38], fine-tuned, and saved as a texture (Fig. 35). Maya uses a utility node called *Bump2d* to read the texture and convert it to "perturbed normals" in order to create a bump map. The *Bump2d* node can be connected, via the *outNormal* attribute, to the *normalCamera* attribute of the *misss_fast_simple_maya* shader. As all the creases do not appear at once, it may be desirable to produce unique bump maps for each step in the animation. This is done by scanning the paper after individual steps in the folding process and creating distinct shaders for every phase.

Fig. 35. Bump map.

Fig. 36. Specular map.

Although the shader is on its way towards providing a convincing imitation of paper, there is one remaining detail to tackle. Paper is not thought of as a particularly shiny material. In fact, its understated luster is not even noticeable when it is laid flat. However, as the paper folds up, a very slight specular highlight is revealed along the creased edges. A specular highlight is a type of reflection that occurs when light hits a shiny surface. While it is possible to adjust the specularity of the *misss_fast_simple_maya* material, it is difficult to light the paper so that it has attractive, and accurate, specular highlights. Fortunately, a specular map can be employed to control the sheen of the paper. This map can be created by reusing, with a little contrast adjustment, the same scanned image that was used for the bump map (Fig. 36). The texture file is then fed into the misss_fast_simple_maya's specular attribute, thus forcing the specular highlight to appear only along the edges of the paper. At this point all of origami paper's principal aesthetic qualities have been addressed and the completed shader (Fig. 37) can be attached to the model and rendered with mental ray (Fig. 38). A selection of frames from the final animated sequence is shown in the following image (Fig. 39).

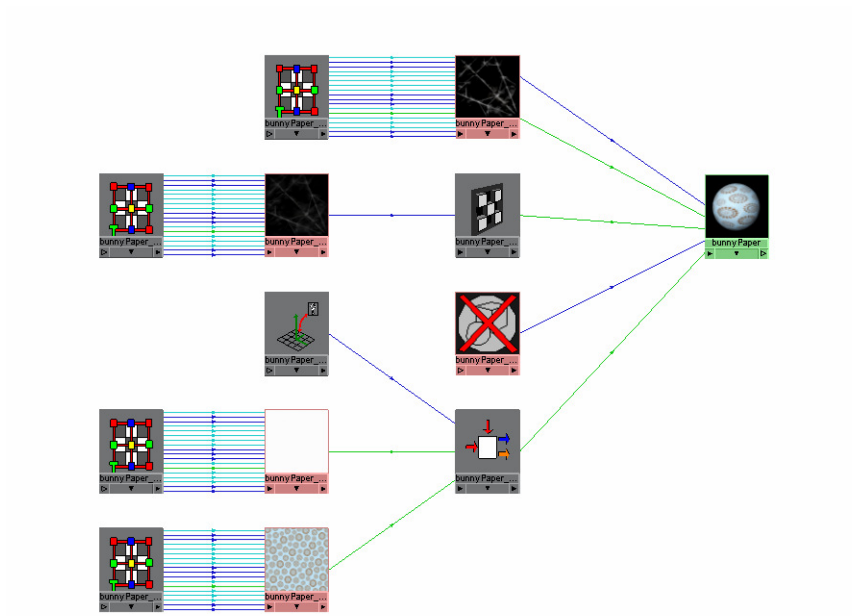

Fig. 37. Basic shading network for origami paper.

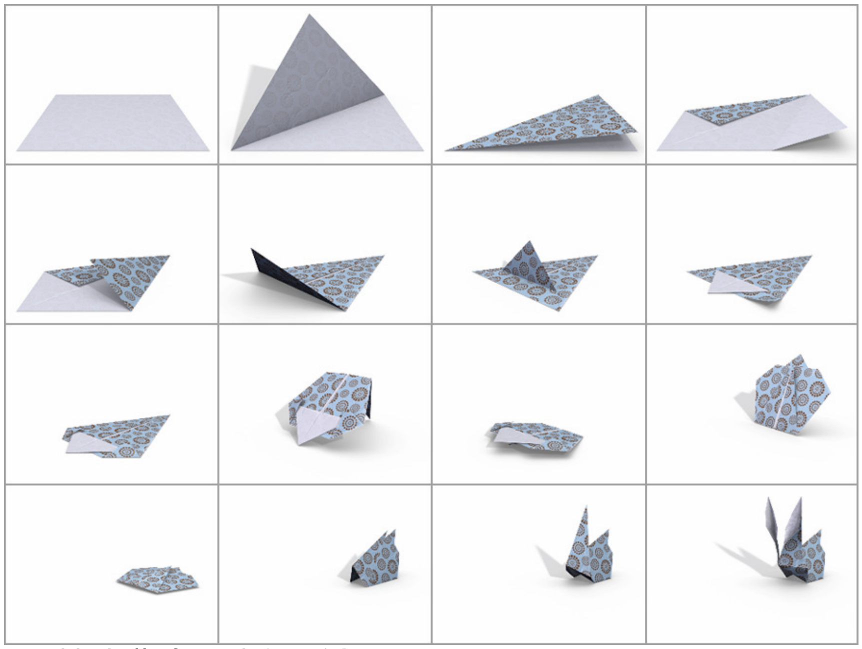

Fig. 38. Stills from *Origami Bunny*.

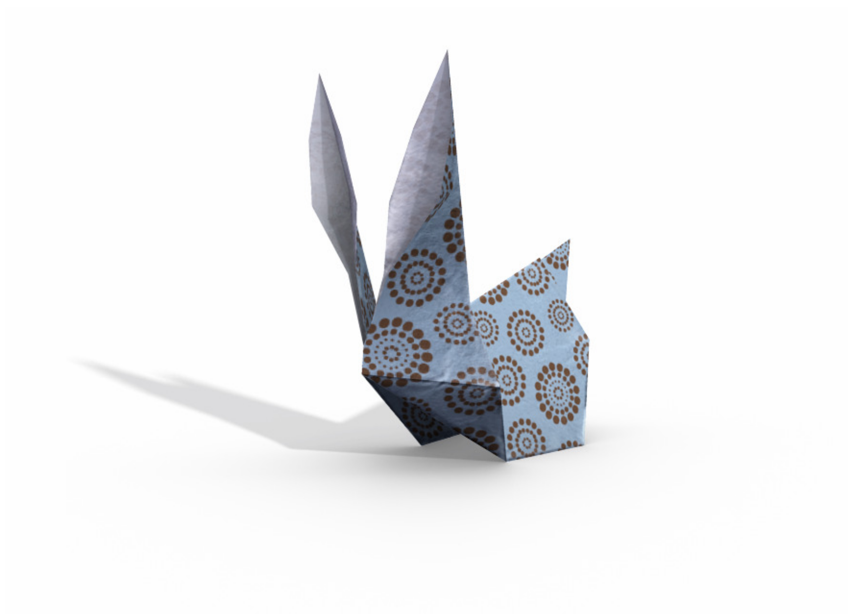

Fig. 39. *Origami Bunny*.

CHAPTER IV

IMPLEMENTATION AND RESULTS

When Pigs Fly… is an original 3D short which applies the methodology discussed above towards the creation of an origami-based animation. This animation serves as an additional evaluation of this thesis' effectiveness by employing the techniques developed for CG paper folding to a variety of origami character designs. This implementation chronicles the production process, from story and concept development to the rendering of pivotal scenes.

WHEN PIGS FLY…

The narrative itself focuses on a piece of paper that forms a character I have taken to calling "Pigasus" [39], who is trying to find his place in the world. Pigasus is creased and more than a little dilapidated; there is a sense that this is not his first time wandering about, trying to fit in. When he comes to rest in a farm yard, Pigasus attempts to make friends among the various origami animals he encounters. Being a piece of paper, he decides to fold himself up to mimic the first creatures he sees, a trio of boisterous pigs. Unfortunately, Pigasus is made from a differently patterned paper and is instantly recognized as an outsider. He is roughly rejected by the pigs and then, by each and every one of the other animals that he meets and seeks to befriend. By the end of the story, a dejected Pigasus has just about given up hope when he comes across a yellow butterfly, which also happens to be made from the same sort of origami paper. Inspired, Pigasus folds into a butterfly and the two fly off together.

The story functions as a child-like fable, as well as a take-off on a familiar idiom. The phrase "when pigs fly" is a humorous way of saying that something is impossible and can never happen. Here, in addition to having a literal interpretation, the story plays on the transitive qualities of paper. A blank sheet of paper represents endless creative potential; it can be written on, drawn on, crumbled up or folded into anything and everything. Thus, it is only on account of paper's perpetually malleable nature that a "pig" could ever "fly."

PRODUCTION DETAILS

Although storyboards were created to narrate the entirety of the paper's adventures, only the first few shots were fully animated and rendered (Fig. 40). Finalizing the entire piece was both beyond the scope of this thesis and unnecessary in terms of assessing the CG paper folding methodology. These opening shots were selected to establish the mood and style of the piece. In addition, they contained the only scene where the paper is folded from a flat sheet into a finished origami model without any cuts or edits between steps.

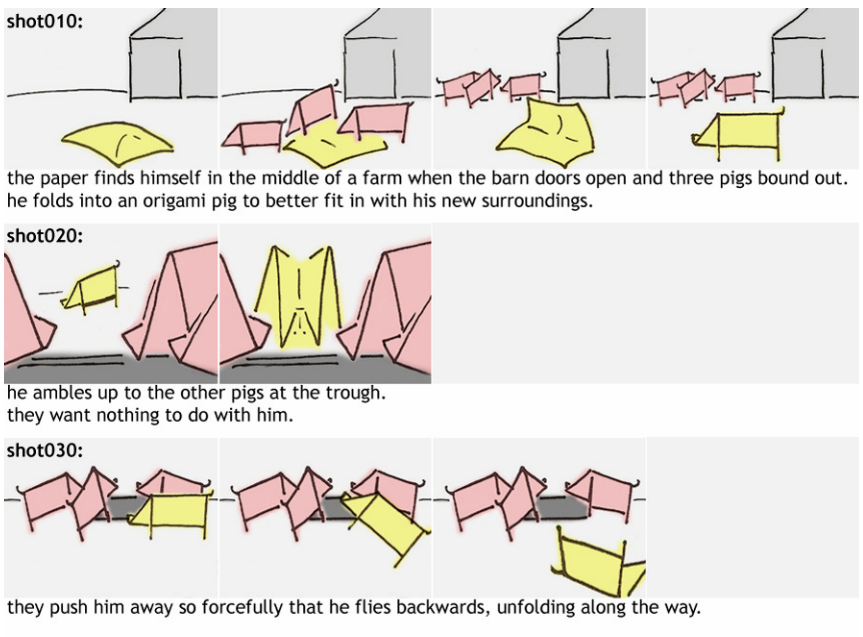

Fig. 40. Storyboard for shot010 through shot030.

Concept Art

At the beginning of the production process, concept art was created to convey the visual look intended for the animation. Because every element, from characters to setting, was meant to appear as if it were made out of paper, careful attention went into selecting papers that would be complementary to each other. Origami paper has traditionally been available in solid and patterned varieties, with the array of patterns ranging from plain (simple gradations of two colors) to ornate (kimono prints with foil embellishment). However, most of the commercially available origami paper has an oriental flair that does not fit in with the style desired for this piece. Instead, the patterns chosen were inspired by scrapbook paper, which was both more colorful and more in keeping with the playful and exuberant mood of the film (Fig. 41 through 44).


Fig. 41. Concept art, example 1.

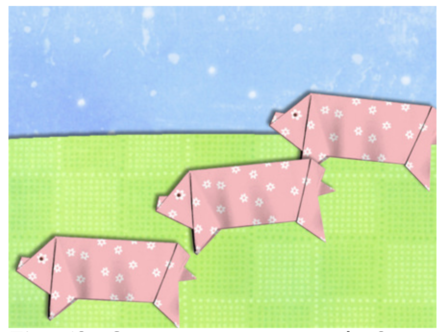
Fig. 42. Concept art, example 2.

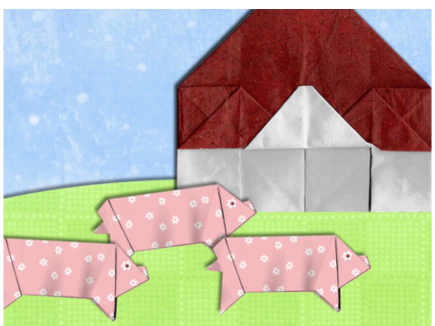
Fig. 43. Concept art, example 3.


Fig. 44. Concept art, example 4.

Modeling

The models required for these scenes included a trio of pink pigs, various set elements, and a piece of paper capable of folding into an origami pig. Because of the disparity between folding and non-folding models, slightly different tactics were employed in the creation of each.

The piece of paper was formed by following the approach described in the methodology section of this paper (see page 13). The model started out as a flat, 4 x 4 inch polygonal plane which was then subdivided to reflect the final crease pattern of the origami pig model (Fig. 45). Since the paper is actively folded into a pig during the animation, this is all that is needed in the modeling stage. The folding process itself is detailed in the following section.

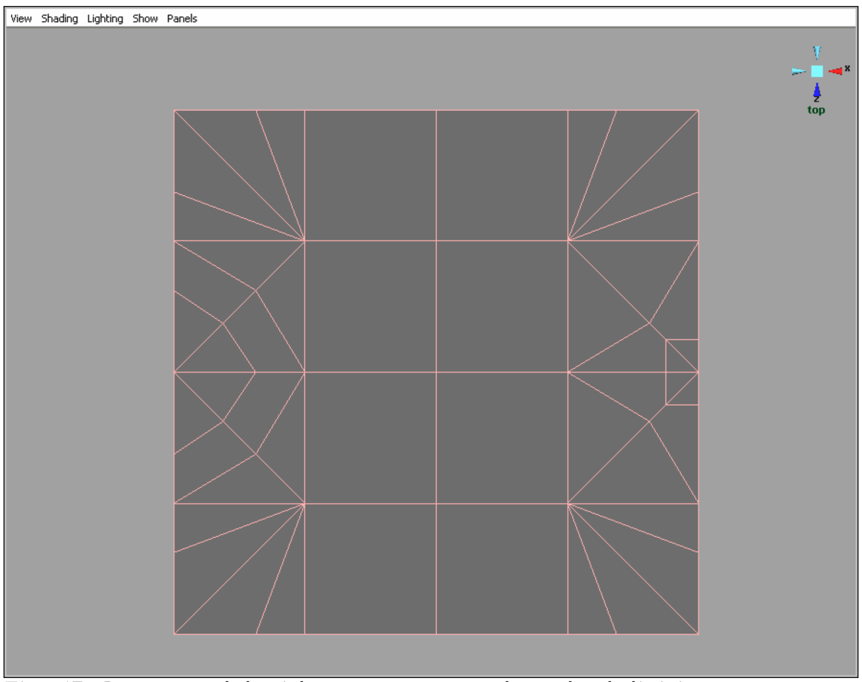

Fig. 45. Paper model with crease pattern based subdivision.

Once the pig was folded, its model could be duplicated and used as a basis for all three of the non-folding pink pigs (Fig. 46). The eyes, as well as extra creases and wrinkles, were added at this point with the intention of providing each character with a distinctive look and personality. The individual planes of the model were also extruded to give the paper some thickness and eliminate any unrealistically sharp edges (Fig. 47).

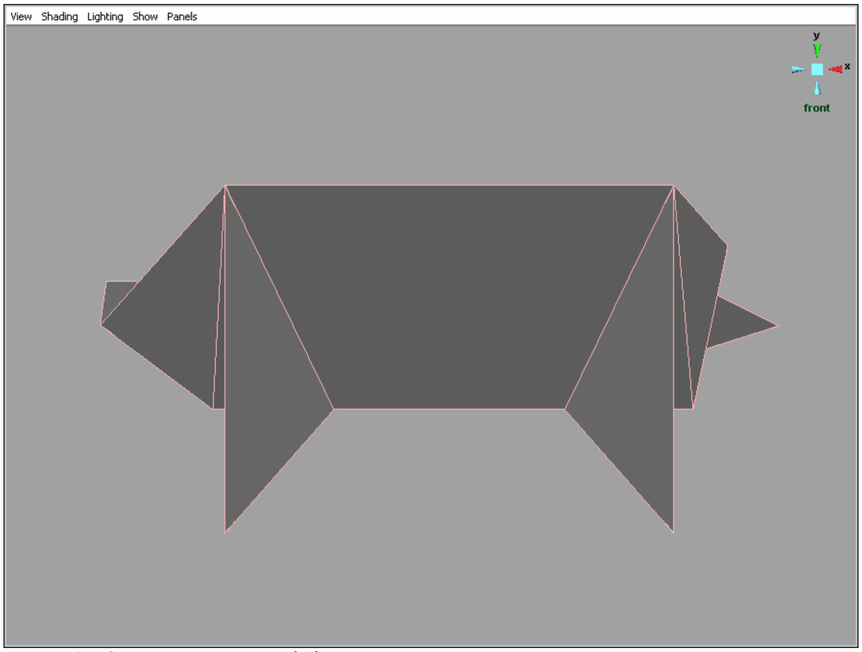

Fig. 46. Origami pig model.

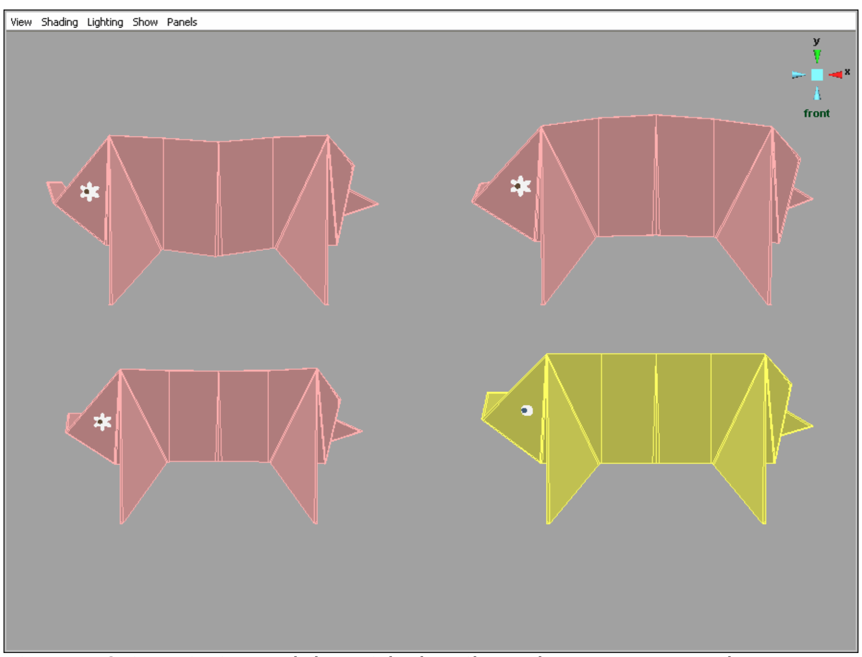

Fig. 47. Origami pig models, with details such as creases and thickness.

Modeling for the major set pieces followed the same general construction techniques. The barn and trough models started out from “creased” or subdivided planes, and joints or clusters were employed to fold and shape the paper into place. However, because the folding and unfolding of these pieces is not shown onscreen, there was no need to animate the process. This made it feasible to use just one model all the way through since, by deleting the various deformers after they were used, one could eliminate the various transformation effects caused by multiple deformers operating on the same vertices. In addition to the barn and trough, a ground plane (modeled to suggest a slightly crumbled piece of paper) and several blades of paper “grass” were added to round out the barnyard set (Fig. 48).

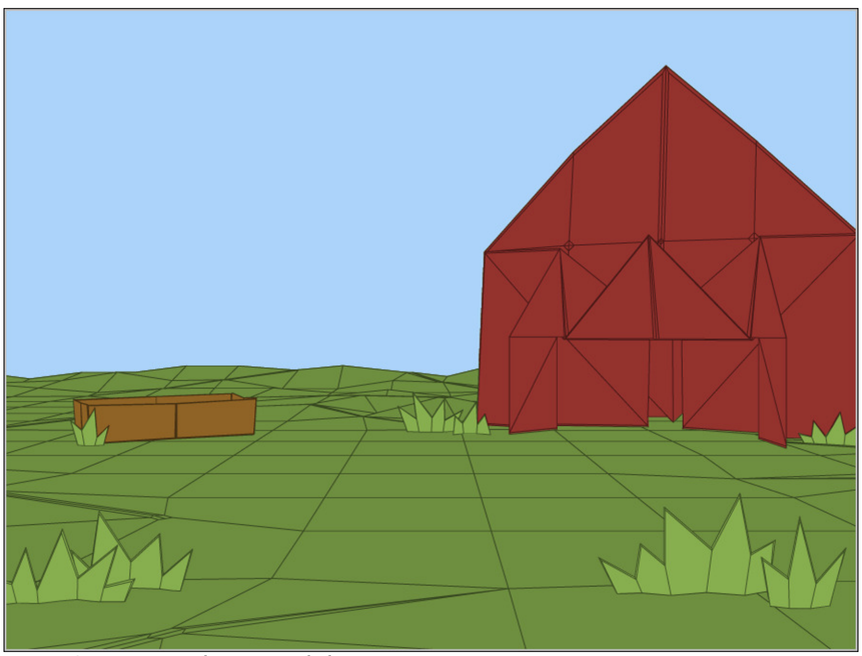

Fig. 48. Barnyard set model.

Rigging and Animation

Rigging or character setup was required in order to animate the paper, the final, folded pig, and the three pink pigs. Of course, rigging for such disparate types of motion required completely different approaches. The non-folding models needed to be capable of running, walking, and snorting; movements well-suited to traditional skeletal animation. Meanwhile, the piece of paper had to be capable of folding from a flat plane into an origami pig. For this, the same general methodology used to create an origami bunny was employed.

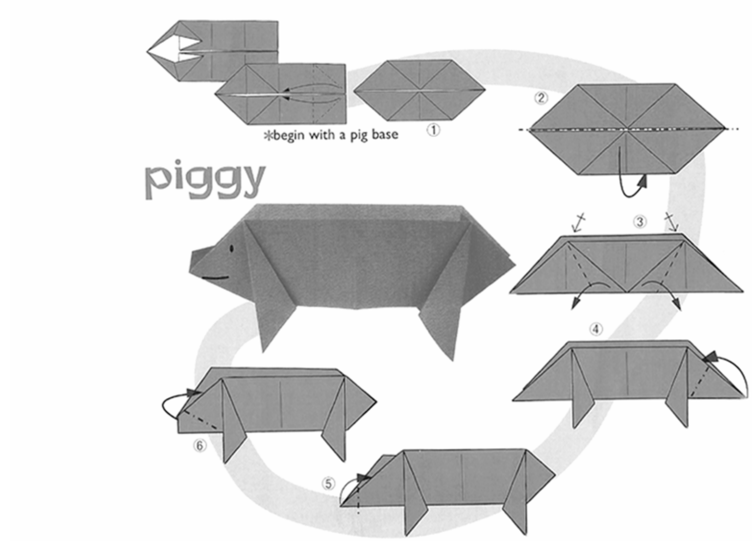

Fig. 49. *Piggy* from *Origami: Page-A-Day Calendar*, Margaret Van Sicklen, 2007.

The directions from a linear origami diagram were followed in order to shape the paper into a pig [40] (Fig. 49). As with the bunny, cluster deformers proved to be the most useful tool for manipulating the model. Starting with the first fold, one or more clusters were applied to a small set of points based on which vertices were going to be affected (or moved) in that step. Next, the pivot point of each deformer was adjusted so that the axis of rotation would be centered in the correct place. The rotation attributes (either X, Y, or Z) for the cluster were then keyed to show the paper, first in its original pose, and then in its position post-folding. It is important to note that, once again, a lot of care had to be taken to prevent the various planes from intersecting with each other as the paper folded. This problem was dealt with by either carefully adjusting the rotation values or by including additional cluster deformers which worked to pull the troublemaking planes away from each other.

After the clusters had been keyed the model was duplicated in its post-folding state for use in the next step. Duplication of the model was necessary to prevent double transformation effects. New clusters were then applied and keyed to imitate the next fold. This process of creating clusters, animating them, and then copying the model was repeated until every step in the diagram had been completed. Then, the visibility attribute for each model was keyed to create the appearance of a single model transforming itself from a flat piece of paper into a folded up origami pig. The resulting models and rigging mechanisms are dissected in the following image (Fig. 50).

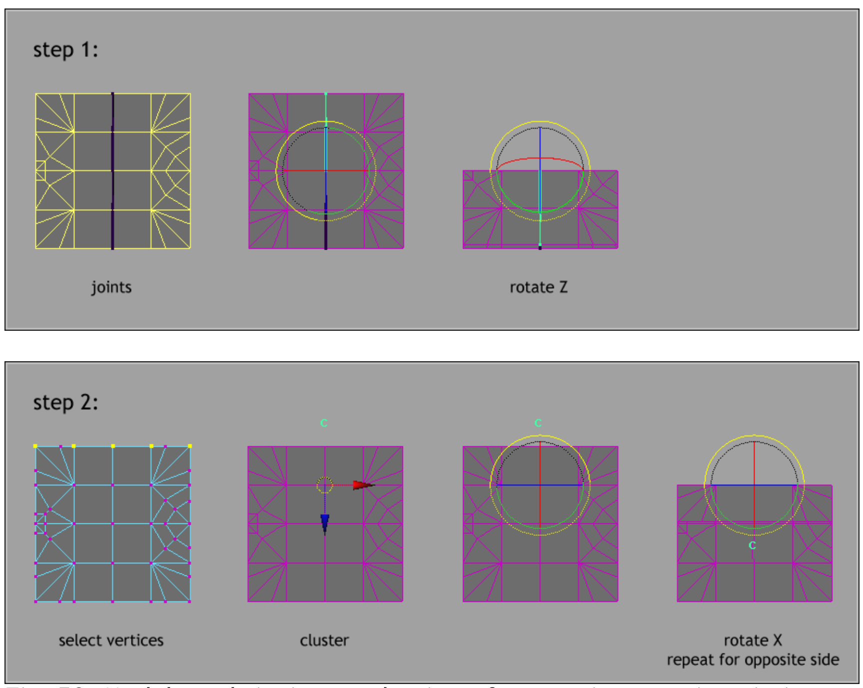

Fig. 50. Models and rigging mechanisms for creating an origami pig.

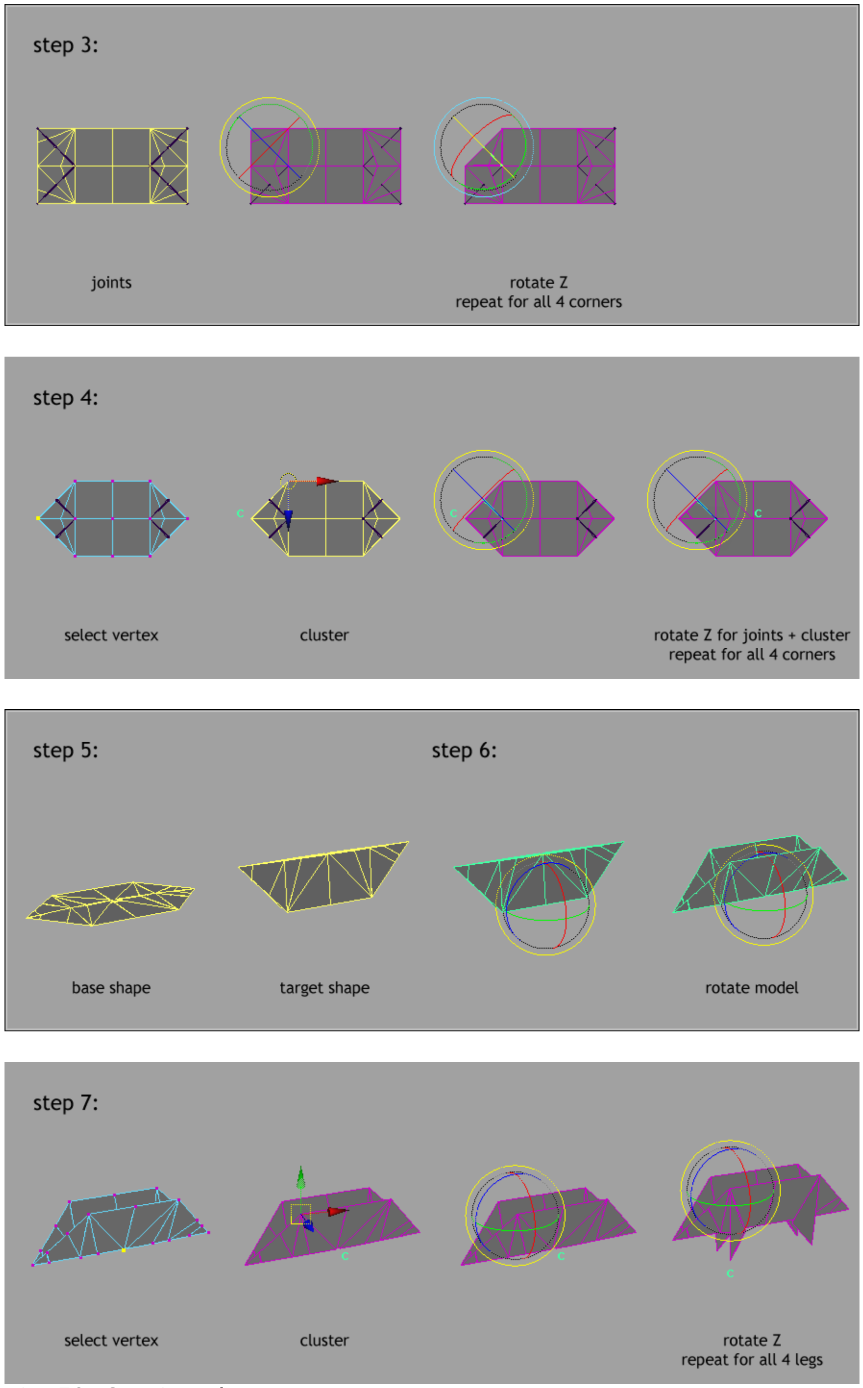

Fig. 50. Continued.

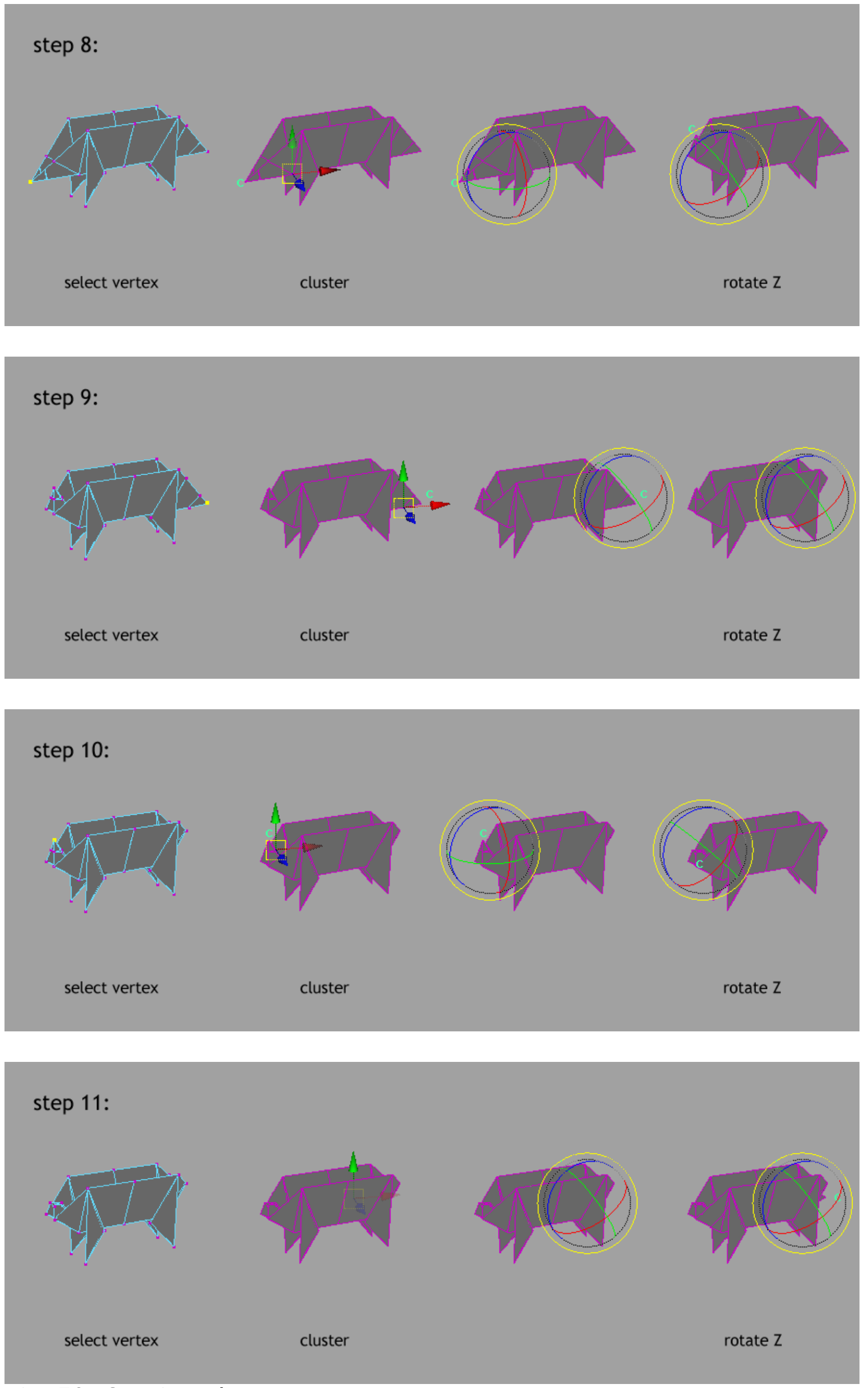

Fig. 50. Continued.

There were some minor variations in the techniques employed in folding the pig versus those used in folding the bunny. For instance, in the pig's crease pattern most of the major folds were oriented across either the horizontal or vertical axes, whereas the bunny featured many creases along the diagonal. Another distinction could be seen in the different types of folds needed to create the origami pig as opposed to those seen in the bunny diagram. These included the squash fold, the reverse fold, and the crimp fold. Every new fold called for a slightly different approach, thus requiring one to think anew how to position and rotate the various cluster deformers. Furthermore, although the pig had more folds than the bunny overall, there was greater potential for merging several steps into the same CG model. As long as the clusters were not affecting the same vertices, they could be combined. This was helpful because many of the pig's folds were repeated, first on one side and then on the other.

The three pink pigs and the final, folded origami paper pig were more conventionally rigged via a system of joints and bones. The skeletons for these followed the essential bone structure of an actual pig, but at the same time took into account the uniquely simplified structure of the paper models. The general idea was for these characters to be animated in a way that was stylized but still recognizably pig-like. The models were bound to the appropriate skeletons and the default skin weighting was adjusted to better control each joints' influence over the mesh. Deformers were added to every pig to create effects that were not integrated into the skeletal system itself. These included wiggling tails, moveable snouts, and overall squash and stretch controls that would help give each pig a slight spring in its step. A simple user interface comprised of assorted NURBS shapes was created to make the animation process more intuitive and the controls easier to key (Fig. 51).

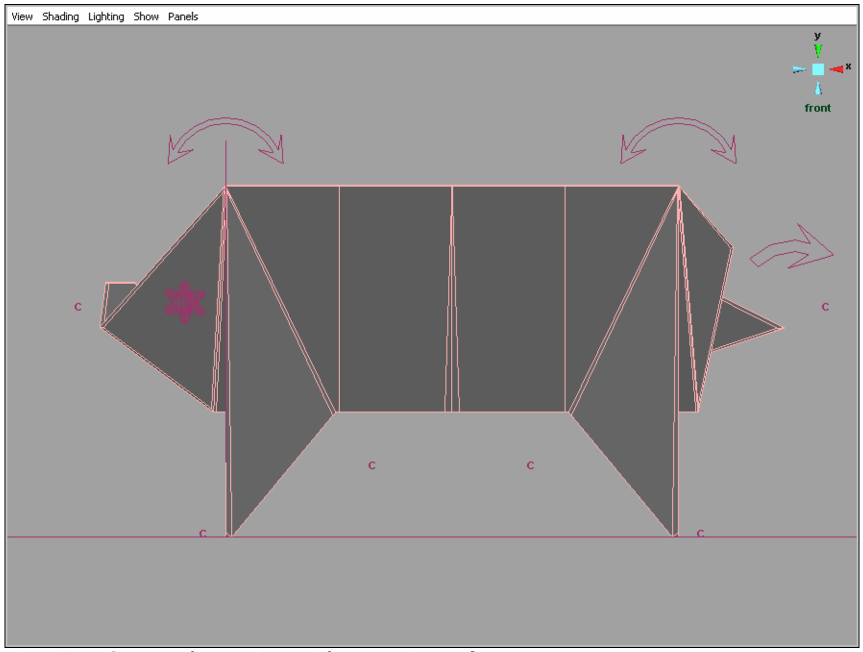

Fig. 51. General pig rig with user interface.

Shading and Lighting

The shading network produced for the bunny was used as a template for developing paper-like surface materials for all of the objects in the animation. Since each of the story elements was meant to be crafted from folded paper, this was a resourceful and practical solution. By making small modifications to individual attributes (such as such as *SSS Color*, *SSS Weight*, etc.) and swapping out the various texture, bump, and specular maps, it was possible to create shaders that were unique to each character and set piece.

Of course, any effort to create appealing and realistic shading would be useless without sufficient lighting. The lighting for this animation needed to depict the bright, clear, mid-morning day on which the story takes place. To do this, Global Illumination and Final Gather, two mental ray rendering techniques, were employed. Global Illumination is the general name which describes several algorithms used to calculate a scene's indirect, or reflected, illumination. mental ray uses photon mapping to replicate this natural phenomenon. Photons are emitted from a light source and tracked as they bounce from surface to surface, scattering energy around the scene until ultimately being absorbed [41]. mental ray's indirect illumination also includes a Final Gather calculation that imitates the subtle color bleed seen when a surface casts its own hue onto nearby objects [42].

Producing the lights to facilitate these effects was straightforward and required only minor deviations from more basic lighting setups [43]. First, a spot light was carefully placed to reproduce the effects of sunlight. As the main source of illumination for each shot, this light bathed the entire setting in a warm orange glow and was responsible for casting the principle shadows. Next, a large NURBS sphere was added to enclose the whole barnyard. This sphere, assigned a sky colored shader with a high incandescence, provided the light rays with an object to bounce off of and at the same time imparted a very slight, dusky blue tinge to the entire set. To finish, a point light was strategically placed in the rear of each scene to provide backlighting. This was needed to activate the sub-surface scattering effect already incorporated into the paper shader. The Global Illumination and Final Gather settings (located within the Render Globals) were then activated and tweaked, with the final result being a fully sunlit and textured environment with an added realism not seen in more conventionally lit renderings (Fig. 52).

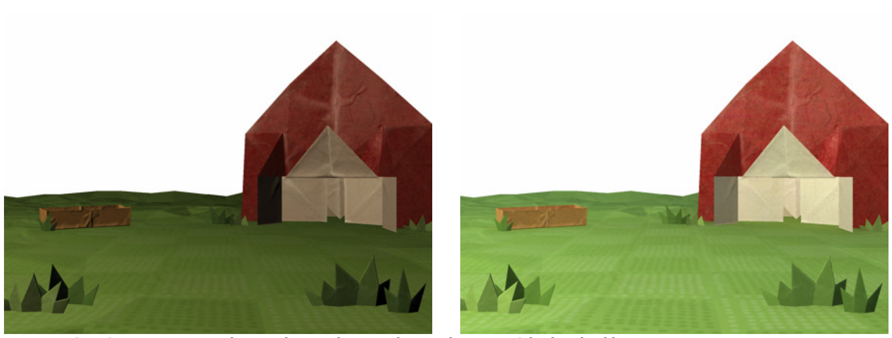

Fig. 52. Scene rendered with and without Global Illumination.

Rendering and Post Processing

All of the animation sequences were rendered using the mental ray plug-in for Maya. Each individual shot was rendered in two different passes (Beauty and Shadow) in order to allow for greater flexibility when compositing the images together. Additionally, the background and foreground elements were broken up into different layers whenever possible. This was done in order to speed up render times and prevent unnecessary re-rendering of static objects. All of the passes (Fig. 53) were ultimately brought into After Effects [44] where they were combined with a background image of a scrapbook paper sky (Fig. 54).

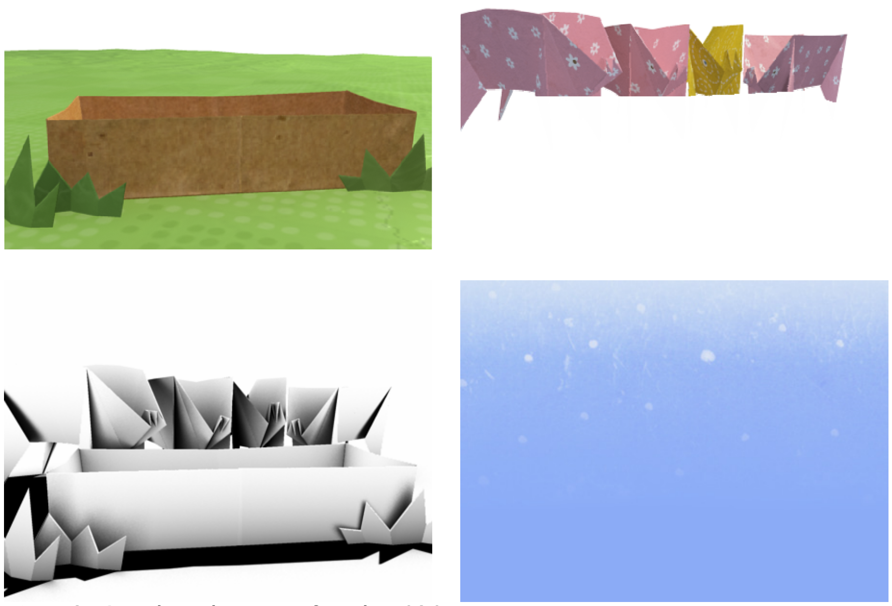

Fig. 53. Rendered passes for shot020.

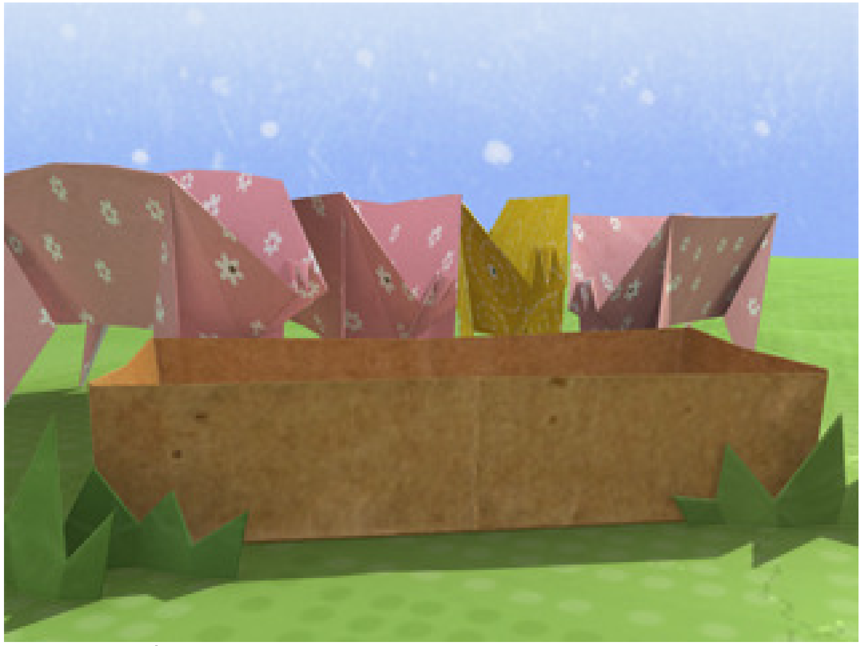
Fig. 54. Final composite.

The post-processing involved in this animation was minimal. The shadow color was altered slightly, changing from a rather severe black to a rosy blue in an attempt to better match the color palette for this time of day and to keep the shadows from appearing overly dark. The overall color of each frame was also subtly adjusted in order to be consistent from shot to shot (Fig. 55).

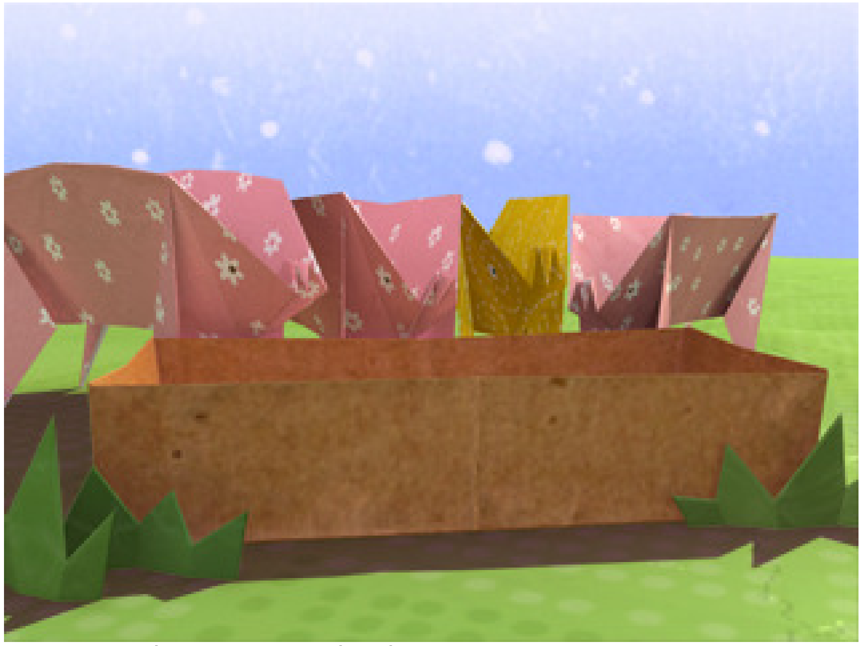

Fig. 55. Final composite with color correction.

RESULTS

The final product of this thesis is an excerpt from *When Pigs Fly…*, an original 3D animation. Featuring an origami-based narrative, the resulting short demonstrates the CG paper folding techniques developed during the course of this research. To test these techniques every element, from the characters to the background set pieces, was modeled to appear as if crafted from a sheet of paper. In addition, the main character actively folds itself into a variety of different origami creations throughout the course of the story.

The CG folding approach utilized was not without its limitations. The effort required on the part of the user to not only keep track of the various models, but also to determine crease pattern geometry, assign appropriate pivot points, and avoid planar intersections made implementation almost prohibitively difficult. This brief excerpt alone required almost ten models and more than twenty unique rigging mechanisms to accurately represent the transformation of a piece of paper into an origami pig.

In spite of these shortcomings, the results were successful according to the terms laid out for evaluation. The final animation depicts the paper in a way that is both physically correct and convincingly realistic. Every step was fully animated and no portion of the folding process was omitted. Great care was taken to maintain the paper's physical geometry, a quality that had been frequently disregarded in prior works. From an aesthetic standpoint, the final renders closely match the original concept art. The bright colors and scrapbook inspired patterns are satisfactorily captured by the assorted shaders, which create a reasonable facsimile of actual pieces of paper. Most significantly, the general methodology proves itself adaptable to a wide variety of origami figures, making it a valuable template for future projects which seek to unite origami with computer graphics. Several still images from the animation are presented below (Fig. 56 through Fig. 58). Additional artwork created in support of this thesis can be found in Appendix B.

Fig. 56. Still from shot010.

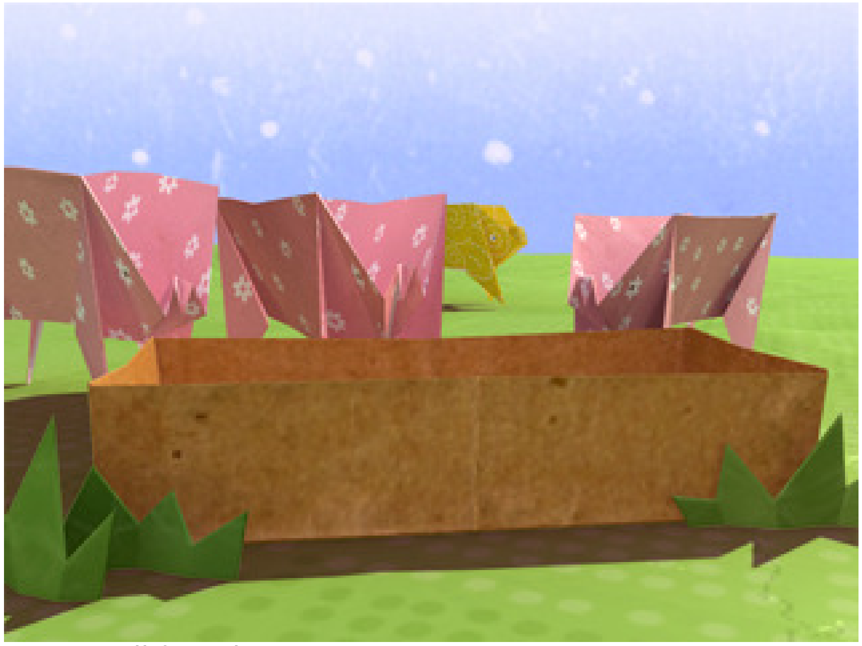

Fig. 57. Still from shot 020.

Fig. 58. Still from shot030.

CHAPTER V

CONCLUSION AND FUTURE WORK

CONCLUSION

This thesis successfully implements a technique for folding an origami model in Maya. The stated goals of this project, to maintain the paper's original geometry, to animate each of the steps involved in the creation an origami model, and to realistically portray both the paper and the folding process, were all met. Moreover, the methodology proved itself to be adaptable to a variety of origami figures, making it a viable tool for use in my 3D short, *When Pigs Fly…*, as well as future projects concerning paper folding.

FUTURE WORK

There are many opportunities for further development within this thesis. One simple extension would be to modify the animation so that it functions as a tool for learning how to make origami. This could easily be done by slowing down the motion and re-framing the paper to more clearly illustrate how it is folding. Because origami diagrams can be notoriously tough to interpret, an instructional sequence could be very useful, especially for mastering some of the more difficult or confusing moves.

A more substantial improvement would be to resolve some of the problems encountered when attempting to fold the paper in Maya. While the techniques pursued in this thesis create an acceptable final result, the use of different models for each step in the folding process is a rather inelegant solution. The cultivation of a single model that could go from a flat piece of paper to an intricate origami design would be both practical and more user-friendly. Given that the research and development phase exposed several fundamental limitations in Maya's ability to accomplish this, it would probably be necessary to look outside the software for an answer. Alternately, a MEL (Maya Embedded Language) script or plug-in could be created to extend the 3D modeling package's capabilities and allow the paper to be animated in a more straightforward manner. Eventually, such a tool could be further enhanced to prevent planar intersection and possibly even allow some automation of the folding process.

Finally, the concepts explored in this project can potentially be applied to subjects that, on the surface, seem to have little to do with paper folding. In the past origami has been used as an inspiration for unraveling complex puzzles in areas such as robotics, manufacturing, architecture, and computer science. Essentially any conundrum involving an object that must exist in two states (one flattened and one folded) has a potential solution rooted in origami. For this reason, the methods developed in this thesis could be effective in constructing CG renderings or computer simulations which might help to test origami-based solutions to diverse and seemingly unrelated problems.

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APPENDIX A

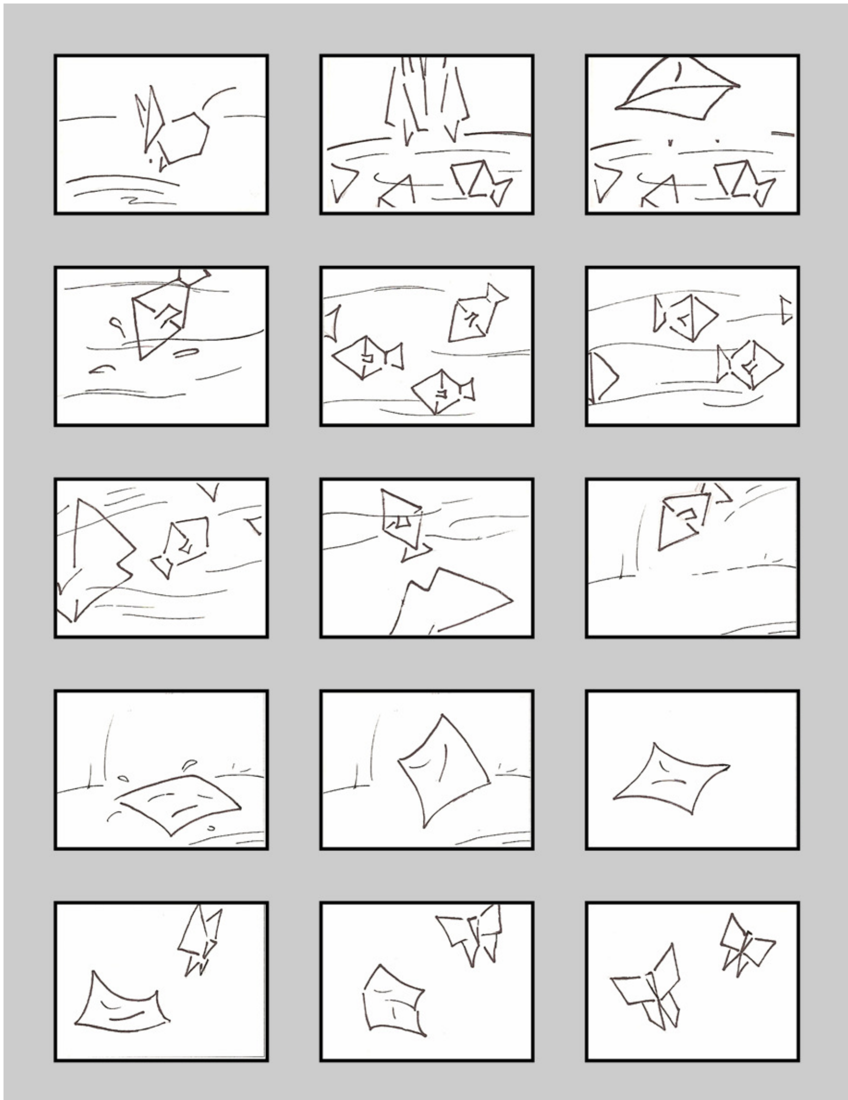
The following QuickTime movie files are included as attachments:

- Skeletal Animation Test: jointsTest.mov
- Blend Shape Test: blendsTest.mov
- Cluster Deformer Test: clusterTest.mov
- *Origami Bunny*: bunnyExample.mov
- *When Pigs Fly…*: pigsFinal.mov

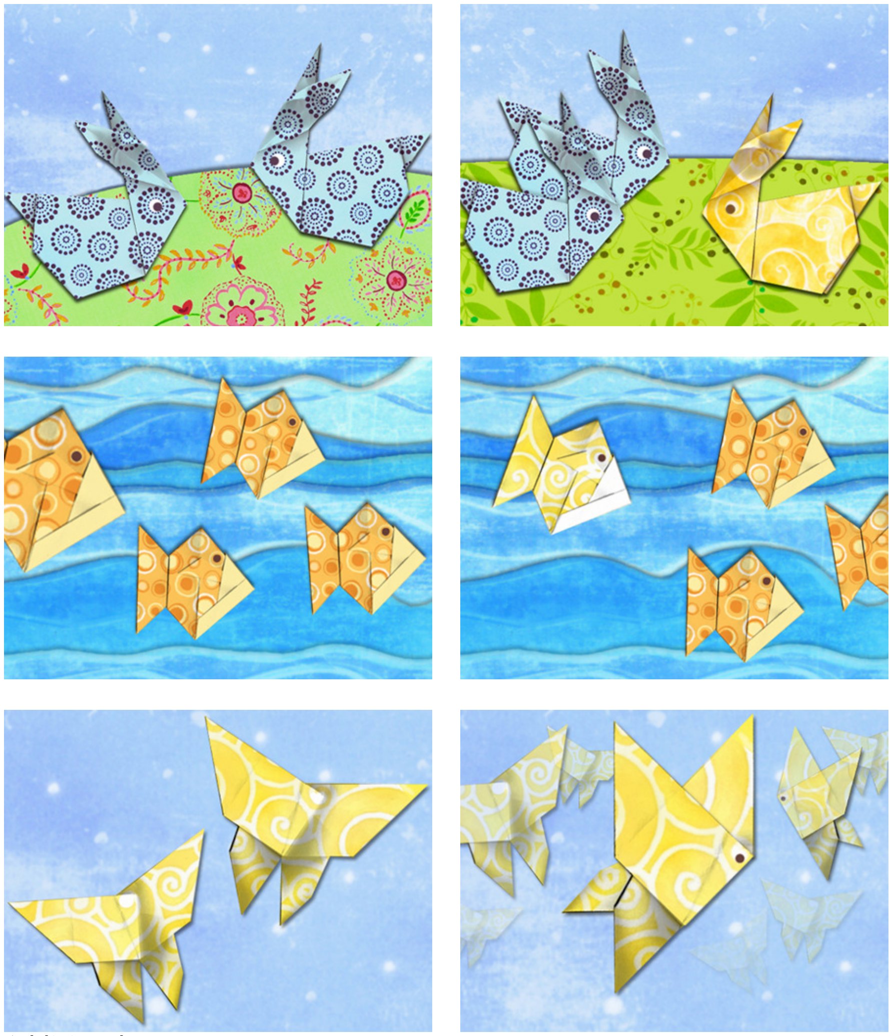
APPENDIX B

These additional images were created in support of this thesis:

When Pigs Fly… Storyboard.



When Pigs Fly… Storyboard, continued.



Additional concept art.

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