

**INTERACTIVE THIN SHELLS – AN INTERFACE FOR  
THE ANALYSIS OF PHYSICALLY BASED ANIMATION**

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Master of Science in Computer Science

by

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# Abstract

## **Interactive Thin Shells – An Interface for the Analysis of Physically Based Animation**

James Ross Skorupski

With the advent of real-time physically based animation over the past decade, and more recently, the growth of general mathematical computing on graphics processors, there has been an increasing interest in the development of realism in computer graphics. However, the algorithms involved in mimicking the physical world are often very complex, abstract, and out of reach for an average computer science student or practitioner. This work introduces an interface to a physically based algorithm, a thin shell animation, which focuses on visualization, experimentation, and control. Through the use of dynamic coloring, abstract visual cues, robust user interaction, and full control over the algorithm parameters, our system facilitates the process of discovery and experimentation, which can enhance the learning experience and help overcome the difficulties in understanding the mathematically intense concepts that comprise the core of many physically based models. Furthermore, our interface design can be used as model for interacting with other types of physically based animations and provide the same benefits for learning.

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# 1 Problem Description and Motivation

One of the many current driving goals in the field of computer graphics is to artificially replicate reality by mimicking the appearance of natural objects and phenomena. While the ultimate purpose of the resulting imagery may vary widely from entertainment to scientific endeavor, the underlying algorithms that produce the imagery of interest are, more often than not, based on our basic scientific understanding of the world around us, and therefore mathematically intensive. These algorithms and their associated techniques, which often deal with real world phenomena such as fluid dynamics, rigid body dynamics, and the transport of light, are grouped into a subset of computer graphics known as *physically based modeling* [1]. The complexity of these algorithms is often proportional to the desired amount of realism and the level of mathematical knowledge and experience required to understand and successfully implement these algorithms can often exceed the capabilities of a typical computer science practitioner. Furthermore, these programs ultimately can only discretely approximate the continuous nature of reality, and are therefore guaranteed to introduce some level of error which must be understood and dealt with appropriately.

While traditionally, modeling the physics of reality has been delegated to large clusters of servers computing over the course of hours or days, the rapid advancement in processing power and memory storage sizes over the past decade has allowed for relatively complex physically based algorithms to perform at interactive frame rates [1], [2]. In addition, the market for home computer and entertainment console gaming has increased dramatically,

and the quest for realism in computer graphics in general has been hastened by the quest for realism in interactive entertainment. Modern graphics cards manufacturers, similarly driven by the home entertainment market, are beginning to encourage the development of general purpose mathematical computing algorithms specifically designed for the highly parallel stream architecture of graphics processing units, while other hardware vendors are developing dedicated solutions that attempt to accelerate the mathematical operations common in physically based modeling [19], [25]. Together, these technological and financial motivations to develop more realistic computer imagery will inevitably further the interest in physically based modeling, and encourage computer scientists to explore the concepts associated with the field.

As technology advances and more complex physically based algorithms continue to develop and become a feasible avenue for generating computer imagery, the understanding of these algorithms and their underlying concepts will become a greater challenge. In addition, as the demand for realism in the virtual world spreads across all areas of the real world, computer scientists wishing to design physically based algorithms will encounter an increasingly varied amount of scientific theory, ranging from thermodynamics to astrophysics. To make matters worse, previous research has shown that many modern computer science students encounter a small selection of math courses in their curriculum, and therefore tend to exhibit weak mathematical problem solving skills [3], [12], [6]. It is also safe to assume that many modern computer scientists, who are recent university graduates, may be similarly lacking in mathematical background required to understand many of concepts in physically based models.

The problem therefore presents itself: How can computer scientists, students and practitioners alike, better understand the workings of math-intensive computer graphics algorithms without an extensive math background? Our solution cannot eliminate the need for traditional study in the requisite mathematical topics. It does, however, present a tool to augment the learning process, and provide a more interactive and visual experience for a person wishing to understand the behaviors of these complex algorithms.

### ***1.1 Contribution***

This work introduces an interface to a physically based algorithm that focuses on visualization, experimentation, and control, and encourages the exploration, discovery, and understanding of the algorithm as a whole. Through the use of dynamic coloring, abstract visual cues, mouse interaction, and full control over the algorithm parameters, our system facilitates the process of experimentation, which can enhance the learning experience and help overcome the difficulties in understanding the mathematically intense concepts that underlie our specific algorithm. Furthermore, our interface design can be used as model for interfacing with similar algorithms and provide the same benefits for learning. Our system's target audience includes computer science students and computer science practitioners with a desire to understand the complex workings of a physically based algorithm and augment their learning experience with direct, visual interaction.

Our interface is specifically designed for interacting with algorithms in a subset of physically based modeling, called *physically based animation*. This sub-field deals with

the physical dynamics of mass, ranging from fluids to cloth, and involves the calculation of internal and external energies that influence the resulting physical movement of the system. Physically based animation algorithms facilitate a more natural graphical interface, because they mimic physical motion which can be observed and often confirmed in the real world. Other physically based modeling algorithms, such as those that deal with thermodynamics or lighting models, may not lend themselves well to our specific interface, but the general design concepts behind our system may provide a guideline for future work which involves interaction with those types of algorithms.

The program we created to demonstrate our interface is called Interactive Thin Shells (ITS). The underlying physically based algorithm simulates the dynamics of *thin shells*, which are flexible structures that have a high ratio of width to thickness and have an initial three dimensional non-flat shape that affects its energetic reaction to change from that initial shape [9]. Our implementation of the physical system is based on a simplified constraint model based partially off of previous work of in the area of thin shells [9] and mass-spring cloth simulation [4]. We also implemented both an implicit and explicit integration scheme developed by additional work in the area of cloth dynamics [15], [16], [20]. The ITS environment allows us to directly demonstrate how our interface can be used to investigate the properties of an algorithm and interact with it in an intuitive and reasonable manner. In addition, the freeform interactive design of our interface, as is described in Sections 3 and 4, serves to reveal a weakness in our thin shell algorithm and discrete approximations of continuous material properties as a whole.

## 2 Related Work

The Interactive Thin Shells environment aims to provide a highly customizable and intuitive interactive interface to a physically based animation algorithm. It sets itself apart as a tool for those not intimately involved in the implementation details of the underlying physical simulation, and therefore must focus on allowing the user to explore and discover the capabilities of the underlying algorithm. Because the ITS environment itself involves both the implementation of a physical model of thin shells and its unique interface to that same model, it is based on previous work in the areas of physically based animation, cloth simulation, and visual interactive simulation tools.

The thin shell algorithm implementation in ITS is based on a standard physically based animation model, described in detail in the work of Baraff and Witkin [1]. The ITS environment involves the persistent storage of a series of states of the system, advancement of the states using the forces of a chosen dynamics model, thin shells with masses at each vertex in this case, and numerical integration of this progression which results in movement in the simulation environment. More specifically, the underlying model implementation is equivalent to a cloth animation model with some modifications that support non-planar initial configurations and the stiffer internal forces of thin shell materials.

The ITS system also employs implicit integration to progress the simulation, as described Baraff and Witkin in their earlier development of stable, stiff cloth [2]. The backward

Euler step integration scheme is utilized for implicit integration, and the traditional forward Euler step method is used for our explicit integration mode [1]. While it is a more complicated scheme for calculating the next state of the thin shells model, which requires the solving of a large linear system at each step of the simulation, the implicit method provides for numerical stability that is critical in this particular situation [1]. Our particular implementation of the implicit method is based on the work of Dean Marci of the Intel Corporation [15]. Thin shell materials typically exhibit very little deformation within the surface of the material itself, and therefore require high resistance to these local changes in length in area. Because of this, our simulation will experience regions of high energy in response to deformation, where implicit differentiation allows for reasonably sized time steps [1].

Thin shells, as mentioned in Section 1.1, are flexible materials that are extremely thin in one dimension and have a predetermined relaxed non-flat configuration [9]. They typically are very resistant to in-plane deformation, in the form of stretching or shearing, and allow a limited amount of out-of-plane bending from the original shape. Thin shell materials differ themselves from cloth, which is typically modeled with an initial flat configuration and weaker membrane and bending energies. The membrane, or in-plane forces in our algorithm are based on the length of edges between vertices, which is similar to the work of Baraff and Witkin, and the bending force is a simplified form of the piecewise geometric bending energy in the discrete shells work of Grinspun et al [2], [9]. This bending force simplification, which is based on a simple linear constraint across two triangles, is similar to the bending forces of traditional mass-spring particle-based

cloth models, based on the internal structure of many real-world textiles [4]. In addition, the collision and user interaction methods in our simulation are also based on the cloth animation work of Baraff and Witkin [1], [2], which provides a derivation of forces based on arbitrary constraints, as well as direct control of material motion based on manipulation of the mass matrix for the entire simulation.

The user interface of the ITS environment takes the attributes of the underlying physically based animation model and provides a simple, intuitive interface that is aimed not at a programmer debugging code, but designed for an individual who wishes to understand the capabilities and theoretical components of the model. Similarly, Burgoon [5] demonstrated an interface to a thin shell simulation based on origami folding and the discrete shells model of Grinspun et al [9]. The system provided simple user interaction for folding the thin shell, virtual paper in this case, into a new default configuration. Unlike ITS, the purpose of this work, however, was the artistic manipulation of the material, and not the analysis of the inner workings of the algorithm that drove the animation. In general, there is little previous research that addresses an interface design to physically based animation, however, the field of computer-based *realistic* simulation provides another source of research.

The general capabilities of the ITS environment are based on the work of Michael Rooks [21], who defines a set of requirements for general visual interactive simulation (VIS) software systems. VIS systems, as defined by Rooks, simulate real world physical phenomena as accurately and completely as possible, in contrast to the physically based

animation methods such as our implementation of thin shells, which aim to achieve convincing visual realism without a requirement for accuracy. Despite this fundamental difference in philosophies, the goals of tools for VIS systems remain accurate for the ITS environment which is similarly based on experimentation. Rook describes a complete VIS system as one that facilities (1) Intervention, (2) Inspection, (3) Specification, and (4) Visualization, and explains each of these features throughout the paper [21]. The ITS environment satisfies each of these requirements by providing direct control of the meshes involved and procession of time (Intervention), access to and customization of all relevant material and simulation attributes (Inspection and Specification), and visual feedback of the resulting simulation and its effect on the dynamics of the thin shell model (Visualization). The specific details of these requirements and their relation to the design and implementation of the ITS environment are described in Section 3, and the final correlation between the proposed guidelines and the abilities of our system are examined in Section 6.

The work of Rooks also describes the concept of *representative* or *abstract* displays of a VIS [21]. The former is a visualization that is a simplification of a simulation's actual appearance, while the latter is an alternate view of a simulation that may bear no resemblance to its actual appearance, but provides a more comprehensible view of data. In the ITS environment, there is no *representative* display, because the resulting animation of a thin shell is the complete description of the system that is modeled. However, *abstract* displays play an important part in visualizing various local or global attributes of the thin shells model in action, in the form of arbitrary vertex coloring,

dynamic color ranges, and various other visual augmentations of the animation. The specific featured abstract displays of data in the thin shells model will be discussed alongside the design and implementation of this system in Sections 3.3 and 4.3, respectively. The ITS environment therefore combines the techniques of pure simulation tools with an approximate animation model so that a curious student or computer science practitioner is able to discover all aspects of the thin shell model, including its efficiency, capabilities, limitations, and resulting level of visual realism.

## 3 Solution Overview

The ITS solution fulfills the requirements of Rooks [21] for a generalized visual interactive simulation (VIS), by providing Intervention, Inspection, Specification, and Visualization of the underlying simulation. The following section is an overview of the capabilities of the thin shell simulation, the user interface, and the visualization modes available in ITS.

### 3.1 Animation

As described in the related work section of this paper, the physically based animation that runs within the ITS interface is a thin shell model with masses at each vertex, using membrane and simplified bend forces derived from previous sources [2], [9], and employs both explicit and implicit integration to progress the animation. The details of the integration and forces are described in detail in Section 3.1. In order to facilitate the experimental capabilities of the ITS interface, the underlying simulation supports the enforcement of collisions and constraints for the user Intervention requirement, alternating modes of integration, arbitrary mesh file loading, virtual world boundaries, and direct modification of thin shell and simulation parameters to allow for the Specification requirement of a VIS. The system supports constraints on vertices, which disable up to three degrees of translational freedom, which is used by the ITS interface to allow the user to pin vertices in arbitrary locations. In addition, to introduce a varied environment for the thin shell interactions, there is also support for collisions with between the thin shell and sphere or cube environment objects in the virtual world. The thin shell algorithm also is able to switch between explicit and implicit integration modes

without any errors in the simulation as a result of the transition. In order for ITS to allow for a large number of varying thin shell shapes, the simulation is able to load arbitrary mesh files that are formatted in Hugue Hoppe's '.m' format [10]. To ensure that the thin shell objects are not lost in the virtual world, the simulation also enforces boundary constraints at predefined extents along the X, Y, and Z axes. These automatically prevent any mesh from moving beyond a specific region in the simulation.

The final and most important feature of the simulation is its dynamic material and global parameters. The ITS interface is able to access the data inside the simulation and modify any of the thin shell membrane or bend parameters, as well as the time step size, gravity force, integration mode, and environmental collision objects. This modification does not adversely affect the progress of the simulation, and therefore ensures that users are given the most flexible interaction experience possible, to experiment with many simultaneous parameters and observe the resulting effects without interruption.

### ***3.2 User Interaction***

User interaction capabilities of the ITS environment are the only window a user has to intervene in the underlying physically based algorithm. Because of this, we ensured that the interface is simple, clean, and flexible. The user has the ability to start and stop the simulation at will, rotate and translate the camera view, and interact directly with the materials onscreen. When the simulation is active, clicking and dragging on a vertex point initiates a spring force from the mouse location to the vertex of interest, resulting in smooth interaction with the active algorithm. If the user selects a vertex when the animation is paused, he or she may choose to pin or unpin the vertex, which creates or

removes a constraint on that vertex in the underlying physical system. The ITS interface also supports simultaneous experiments. This allows the user to load a single mesh, and generate multiple instances of this mesh with different individual algorithm parameters and shared global parameters. Simultaneous meshes allow the user to perform a comparative analysis of the effects of varying algorithm parameters in an otherwise identical environment. In our specific case of thin shells, the user can vary the behavior of different version of the mesh to behave like rigid plastic, elastic cloth, or somewhere in between. When more than one experiment is loaded, the user interaction between all experiments is linked. This can occur because every experiment has the same thin shell mesh loaded, and a selection of a specific vertex in one experiment can be directly corresponded to a vertex in every other experiment on the screen. As a result, clicking and dragging a point in one experiment upward causes the same upward force on the same vertex in every other experiment that is active.

In addition to interacting with individual vertices, the user is also able to modify any thin shell material parameter, or any one of the many global parameters, such as gravity strength, time step size, and location or existence of environment collision objects. These modifications can occur at any time during the simulation, ensuring complete interface flexibility and total experimental freedom.

### ***3.3 Visualization***

The ITS environment provides two alternative ways to view the simulation. The user may choose to view an abstract, multi-colored representation of the mesh, with varying colors corresponding to force values acting on each of the vertices in the algorithm, and the user

may also choose to view previous states of the animation, stored in memory. These features may also be used simultaneously, to view forces acting at a previously recorded moment in time.

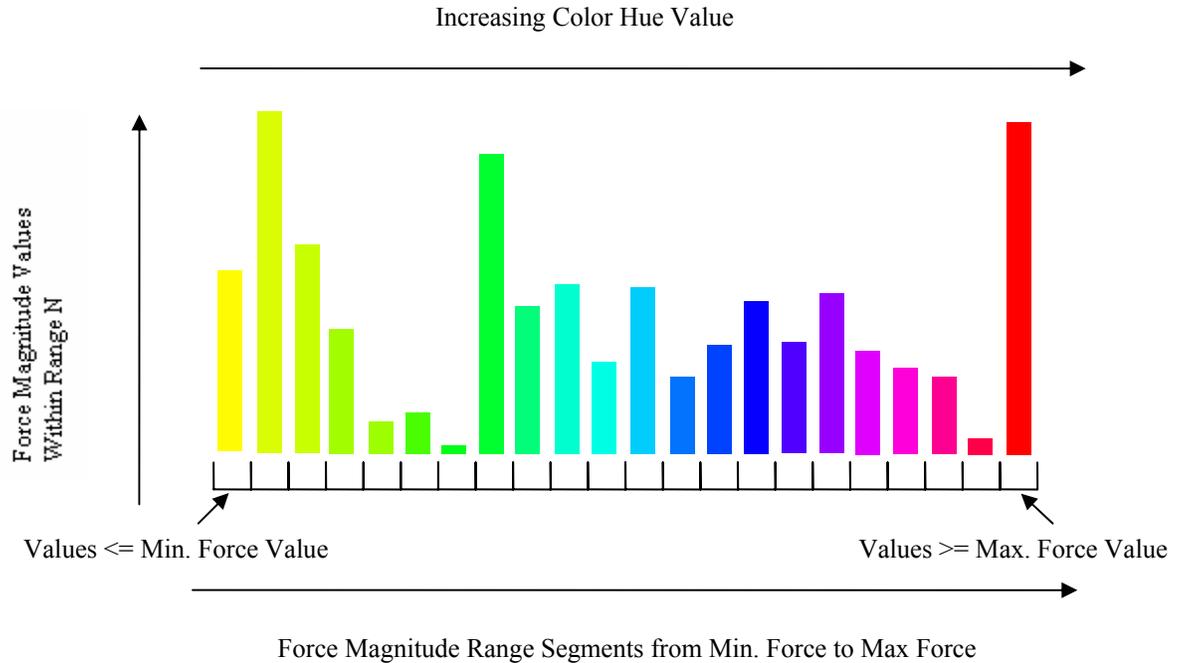
### **3.3.1 Dynamic Histogram**

In the ITS environment, it is important that the user be able to see the various forces acting on the vertices in the simulation, so that he or she may explore the effects of various types of interactions on the animation. Because of this, the user may choose to view the force values for the membrane, bend, or total forces for each vertex within the system. When any of these views are chosen, each vertex is colored according to the location it fits on a histogram, as pictured in Figure 1. This mapping from the large range of possible force values to a series of discrete colors associated with ranges of these values ensures that resulting coloring model exhibits sufficient variations among possible force colors that are large enough to be perceived by the human eye of an ITS user. This is important for analyzing the algorithm at hand and determining areas of interest and performing comparative analysis of different experimental conditions.

The difference between a traditional histogram and the one in the ITS environment is its dynamic range and force-to-color mapping capabilities, which are accomplished through compression and equalization algorithms, respectively. Compression shifts the upper and lower ranges of the histogram in order to attempt to equalize the number of values in each histogram segment, while preserving the equal range increments from one segment to the next. Equalization, on the other hand, performs a non-linear transformation on the underlying force data points in order to spread it across the histogram equally, which

does not preserve the equal range size of segments and therefore relative color comparisons are not reliable [8]. The compression algorithm cannot always choose ideal range values to evenly spread the force values, due to the discrete nature of the histogram, but equalization forces this to occur through a numerical transformation on the original force data, at the expense of uniform relative histogram segment sizes. Therefore, the compression algorithm is useful when relative comparisons between force values must be made, and equalization is useful in discovering areas of small force variation that do not show up on a fixed-size segment histogram. More details on the implementation of these histogram algorithms are in Sections 4.3.1 and 4.3.2 of this paper.

When requested by the ITS user, the compression and equalization algorithms can analyze a single frame of force values or all frames and therefore all force values that have been recorded and are in the simulation cache, which is described later. The analysis of all past and present frame data results in a histogram that is optimized for an entire run of a simulation, and has the ability to show, on average, an adequate distribution of color for any given frame in the animation. In order to analyze all frames of force data, the simulation cache is accessed when necessary to gain access to previously stored state information.



**Figure 1 - A force value histogram, with corresponding hue value mappings**

### 3.3.2 Animation Cache

The ITS application stores a buffer of previous simulation data in a cache so that the user may navigate to a previous time step and analyze the state of the animation. The force coloring option may also be enabled when viewing the cache, so that previous force values can be observed and analyzed. The buffer keeps track of the locations of all vertices in the animation, as well as the total, membrane, and bend force vectors for each of those vertices. In addition, the material parameter settings for each experiment at every frame are stored in this cache, as well the time step and gravity acceleration global settings. In this way, the user is able to see the exact progression of the animation and determine the cause of various behaviors or manipulations in the environment. With

access to a history of all the data that is available at the original animation runtime, useful experiments can be performed and then reanalyzed repeatedly to make useful conclusions.

## 4 Implementation

This section describes the specific implementation of features the ITS environment.

Sections 4.1 through 4.3 describe, in detail, the important or unique capabilities of our software, which directly influence the capability of the system to fulfill the requirements outlined in Section 2. A more complete full feature list, which outlines all major and minor capabilities in the ITS system, is available in Section 4.4. In all mathematical equations in this section, bolded letters signify matrix or vector variables.

### 4.1 Animation

The integration code of the ITS physically based animation is based on the implementation of Baraff and Witkin's implicit cloth simulation by Dean Marci of the Intel Corporation [15]. It has been modified to support a new bending force described in this section, stiffer membrane force constants to replicate the behavior of thin shells, more complex object intersections, and adaptive integration time steps.

#### 4.1.1 Implicit and Explicit Integration

The implicit and explicit integration methods that are implemented in the ITS application are extensively discussed in many previous papers [1], [2]. The equations in Figure 2 govern the progression of our animation. The explicit forward Euler method involves the straightforward computation of new accelerations and velocities by applying the force to the inverted masses of all vertices in the animation, and scaling these by the current time step,  $h$ . This method often results in a diverging system due to the extremely small step sizes required when strong forces exist [1]. On the other hand, the implicit backward

Euler method involves computing the movement of the system by solving for the change in position at a future point in time, based on the expected future forces, which must be approximated by a linear expansion of the current forces. This method allows for much larger time steps, handles stiff constraints effectively, and ensures that the current step is reversible in time, which prevents against numerical divergence [1]. In order to compute the acceleration, or  $\Delta\mathbf{v}$ , one must solve the linear system in the final equation in Figure 2. This is performed using the Modified Conjugant Gradient Method, which is an algorithm described in previous literature that is based on an existing implementation available publicly [2], [15]. In our implementation, the thin shells membrane forces are strong enough to require an explicit adaptive time step that is hundreds of times smaller than the time step used for the implicit method, resulting in slower animation render times, and a small amount of residual system instability that may occur under extreme force conditions in the system.

Explicit Forward Euler Method:

$$\begin{pmatrix} \Delta \mathbf{x} \\ \Delta \mathbf{v} \end{pmatrix} = h \begin{pmatrix} \mathbf{v}_0 \\ \mathbf{M}^{-1} \mathbf{f}_0 \end{pmatrix}$$

Implicit Backward Euler Method:

$$\begin{pmatrix} \Delta \mathbf{x} \\ \Delta \mathbf{v} \end{pmatrix} = h \begin{pmatrix} \mathbf{v}_0 + \Delta \mathbf{v} \\ \mathbf{M}^{-1} \mathbf{f}(\mathbf{x}_0 + \Delta \mathbf{x}, \mathbf{v}_0 + \Delta \mathbf{v}) \end{pmatrix}$$

$$\begin{pmatrix} \Delta \mathbf{x} \\ \Delta \mathbf{v} \end{pmatrix} = h \begin{pmatrix} \mathbf{v}_0 + \Delta \mathbf{v} \\ \mathbf{M}^{-1} \left( \mathbf{f}_0 + \frac{\partial \mathbf{f}}{\partial \mathbf{x}} \Delta \mathbf{x} + \frac{\partial \mathbf{f}}{\partial \mathbf{v}} \Delta \mathbf{v} \right) \end{pmatrix}$$

$$\left( \mathbf{I} - h \mathbf{M}^{-1} \frac{\partial \mathbf{f}}{\partial \mathbf{v}} - h^2 \mathbf{M}^{-1} \frac{\partial \mathbf{f}}{\partial \mathbf{x}} \right) \Delta \mathbf{v} = h \mathbf{M}^{-1} \left( \mathbf{f}_0 + h \frac{\partial \mathbf{f}}{\partial \mathbf{v}} \mathbf{v}_0 \right)$$

Figure 2 - The explicit and implicit integration schemes used in ITS

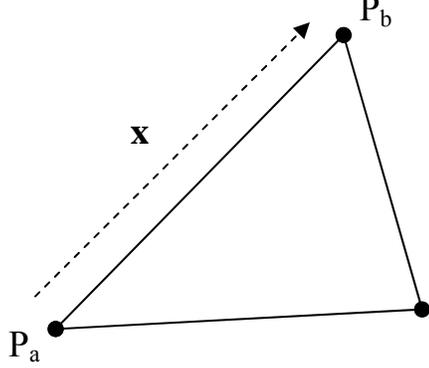
### 4.1.2 Forces and Constraints

The forces that act on the physical system in ITS are a simplified version of the forces that are present in the work of Grinspun et. al [9]. Typically, a thin shell or cloth animation system consists of stretch, shear, and bending forces. The stretch forces reacts to local changes in length (triangle edge lengths), the shear force reacts to local changes in area (triangle area), and the bending force reacts to a change in angle across an edge connecting two faces of a mesh. These forces are often derived from constraint equations that are zero in the initial rest configuration of cloth or thin shell materials [1]. Figure 3 shows the constraint equation,  $C$ , used in both of the forces used in the ITS system. The rest lengths of all forces in our model are determined by the initial relative vertex positions in the loaded mesh model.

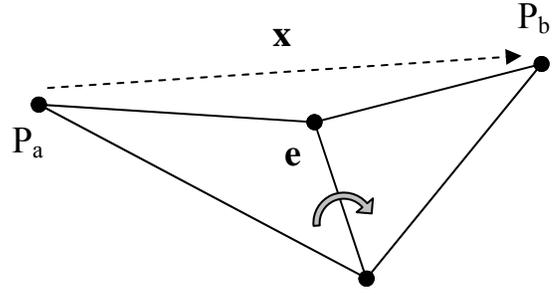
In our implementation, we use very stiff linear constraints between each vertex of each triangle, which prevent both local change in length and therefore any substantial change in local area in such a manner that, in our case, separate stretch and shear forces are unnecessary for achieving the realistic appearance of a thin shell material. As seen in Figure 3, the membrane forces depend on the state of the linear constraint, as well as user-defined membrane force constants, which are modified in the main user interface. The bending force in our implementation is also a simplified form of the bending force appearing in previous work [9]. Instead of calculating the angle change between two faces and applying a normal force on each vertex based on this angle, a simple linear constraint is attached to each pair of vertices that are on opposite sides of a pair of adjacent triangles. This spring-like bending constraint mimics the function of the bending forces found in traditional mass-spring cloth simulations based on a regular grid of interacting particles [4]. This solution is easier to implement, and requires less computation, but has a weakness that is made evident later in this paper. When two triangles are nearly flat relative to each other, the resistance to bending is very weak, because any change in the angle from this flat configuration results in very little change in distance between the two vertices of interest, and therefore very little change in force between these same two points. The original derivation of the bending energy did not exhibit this weakness, due to its reliance on the angle and not linear distance between each pair of vertices involved in the bending energy. A more technical explanation of this weakness appears in Figure 4. On the right side of this diagram is a side view of the bending force across two triangles. The equation for the change in the distance between two vertices with respect to the change in angle between them appears on the bottom left

side of this same diagram. It consists of two cosine functions that act upon the two smaller angles that form the total angle between the two vertices in question. When the total angle approaches 180 degrees, each of the smaller constituent angles approach 90 degrees, which causes each cosine function approach zero. This means that the change in length of the linear constraint also approaches zero, and the bending energy at this angle has very little or no contribution to the total internal force at this point in the thin shell mesh. The original bending force derivation also includes a term which remains in the ITS bending force. The size of the bending force is proportional to  $\frac{\|\mathbf{e}\|}{h_e}$ , which is the length of the edge between the two triangles of interest, divided by one third of the average of the heights of both of those triangles. The analytical source of this term and its relation to thin shell mechanics is examined in detail in previous literature [9]. To prevent infinite oscillation in our animation system, both the membrane and bending forces are also dampened, with corresponding user-defined dampening constants. The results of these combined membrane and bend forces and their effect on the final animation are visible in Figures 9 and 11, in Sections 5.2 and 5.3, respectively.

Membrane Force



Bend Force



$$\mathbf{x} = P_b - P_a$$

$$C = |\mathbf{x}| - (\text{rest\_length})$$

$$\mathbf{f}_{Membrane_a} = \left( -k_m C - k_{m\_d} \dot{C} \right) \frac{\partial C}{\partial \mathbf{x}}$$

$$\mathbf{f}_{Bend_a} = \frac{\|\mathbf{e}\|}{h_e} \left( -k_b C - k_{b\_d} \dot{C} \right) \frac{\partial C}{\partial \mathbf{x}}$$

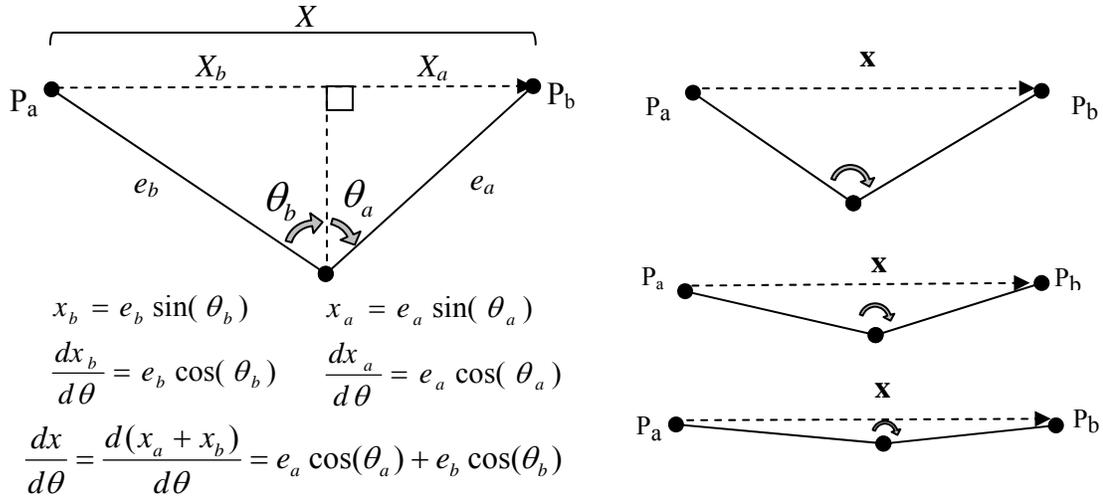
$$\mathbf{f}_{Membrane_a} = \left( -k_m C - k_{m\_d} \frac{\mathbf{x} \cdot (\mathbf{v}_b - \mathbf{v}_a)}{|\mathbf{x}|} \right) \frac{\mathbf{x}}{|\mathbf{x}|}$$

$$\mathbf{f}_{Bend_a} = \frac{\|\mathbf{e}\|}{h_e} \left( -k_b C - k_{b\_d} \frac{\mathbf{x} \cdot (\mathbf{v}_b - \mathbf{v}_a)}{|\mathbf{x}|} \right) \frac{\mathbf{x}}{|\mathbf{x}|}$$

$$\mathbf{f}_{Membrane_b} = -\mathbf{f}_{Membrane_a}$$

$$\mathbf{f}_{Bend_b} = -\mathbf{f}_{Bend_a}$$

**Figure 3 – The ITS Animation Membrane and Bending Forces. Membrane and bending forces have their own force constants and dampening constants, and the bending force additionally relies upon the length of the edge and heights of the triangles across which the force vector spans.**



**Figure 4 - The Linear Bending Force Weakness.** As the angle between vertices A and B flattens, the change in distance between them approaches zero.

### 4.1.3 Boundaries and Object Collisions

Object constraints, their relation to the integration schemes, and their implementation are discussed by Baraff and Witkin [2]. When a vertex of a mesh enters the inside of a collision object, or moves beyond a specified virtual world boundary, it is moved to be just within or underneath the surface of that collision region and constrained along a single axis perpendicular to the surface of contact with the object. If the force perpendicular to the surface of contact is greater than a predefined contact force limit, then the constraint is released and the vertex is allowed to move freely. This prevents the thin shell material from entering deeply into the object of intersection, but also allows for sliding across the region of collision. The contact force on the vertex prevents oscillation of movement and constraint conditions on the surface of collision objects and boundaries, and the result is more realistic animation. Figure 10, in Section 5.2 demonstrates the visual results of these features.

#### **4.1.4 Adaptive Time Steps**

While the implicit integration scheme in ITS is extremely stable and allows for larger time steps and stiffer constraints, it is still possible for it to experience instability in cases of extreme force magnitudes. Due to this potential vulnerability, and the inherent instability of the explicit integration method, the ITS environment supports adaptive time steps, which reduce in size in response to divergent behavior, or large changes in velocity or position. Upon each update of the positions and velocities in the ITS simulation model, if the change in position or velocity exceed a predefined upper bound, the changes are not applied, the time step is cut in half, and the iteration begins again. If the extreme position or velocity changes continue to occur, the time step is repeatedly reduced until it is no smaller than a predefined lower bound. If divergent behavior continues to occur, the simulation proceeds without reducing the time step, allows the errors to occur, and notifies the ITS interface of the problem. However, if a successful iteration occurs, the current time step, if it has been lowered, is increased a very small amount. This allows the ITS animation algorithm to adapt to the current state of the animation automatically, and helps to avoid significant errors in the computation.

#### **4.2 *User Interaction***

As described in Section 4.1, the ITS environment allows the user to modify directly the force constants, dampening constants, gravitational acceleration, time step size, camera views, and environment collision object settings. The implementation of these interactions is straightforward matter. However, the process of allowing the user to interact directly with the animation using the mouse cursor is a more complicated procedure, since it involves modifying the vertex locations and therefore the internal

forces of the thin shell materials involved. The following section discusses the details of the methods used to allow this interaction to occur without algorithm instability and across all experiments running simultaneously the ITS interface.

#### **4.2.1 Live Interaction**

When an animation is currently playing, the user is able to use the mouse cursor to select and move any vertex in any experiment on the screen. Each vertex has an associated spherical “control point”, which can be displayed on screen at the user’s discretion. This control point is a sphere of a fixed radius that represents a volume of space that a vertex occupies. Upon the action of clicking, the ITS interface calculates the vector associated with the selected pixel that emanates from the camera location into the virtual world. This is accomplished using the `gluUnProject` function available in the OpenGL software library, which provides the geometry processing and rasterization framework for our system. This vector is then tested for intersection against all control points in all experiments and the closest intersected vertex is selected. The vector from the selected vertex to the camera then becomes the normal component of a plane located at the selected vertex location. When the user drags the mouse, a new linear constraint with zero rest length is attached between two points - the selected vertex, and the point of intersection between the mouse vector and the previously generated plane. In this configuration, the selected vertex reacts to the attached constraint, while the user-selected intersection point stays firmly fixed in space. The end result is that the user can enact a constraint force and move the particle towards a location that is along a plane perpendicular to the camera ray. This movement algorithm allows for natural interaction that is compatible with any camera rotations or translations. Figure 12, in Section 5.3

later in this paper, visualizes the results of this interaction technique. The vertex of interest cannot be directly moved by the mouse, because the movement would result in very large changes in velocity due to instantaneous and large position changes caused by the finite precision of the mouse location on the screen. These large changes in velocity would potentially lead to numerical instability.

#### **4.2.2 Paused Interaction**

When the ITS animation algorithm is paused, the user may click and select any vertex and choose to “pin” or “unpin” it. Pinning a vertex enforces a constraint with zero degrees of freedom on the vertex of interest, and unpinning a vertex releases any constraints that are currently enabled on that vertex. A pinned vertex cannot change velocity or position in the virtual world. The blue sphere objects in Figure 11, in Section 5.3, represent the locations of vertices that have been pinned by the user using this technique. The user is not able to move the positions of any vertices while the animation is paused, because this would introduce instantaneous changes in position and therefore very large acceleration values that would likely introduce instability in the physical model.

#### **4.2.3 Synchronized Interaction**

Due to the experimental nature of our system, we designed the ITS system to allow simultaneous live or paused user interaction of multiple experiments in parallel. This is possible because all experiments share the same mesh structure. When a user performs a live or paused interaction, the vertex that is selected in the current mesh has the same index into the underlying data structures. Because of this, the ITS environment can easily

attach simultaneous constraints and simultaneous forces on all meshes. When performing live interaction, the ITS program first calculates the interaction with the experiment that was selected with the mouse directly, and then determines the offset of the generated linear constraint in relation to the vertex of interest. This offset is then utilized by all other thin shell meshes to determine the location of the linear constraint points within their local coordinates. The result of this synchronized interaction is a more robust experimental interface that allows very precise and identical manipulation of many experiments in such a way that allows useful comparative analysis. A screenshot of the process of synchronized experiment interaction is displayed in Figure 7 of Section 5.1.

### ***4.3 Visualization***

As mentioned in Section 3.3, the ITS environment allows the user to view the physical model in two different ways in addition to the standard live rendering of the thin shell animation. In the first way, a dynamic histogram colors the mesh surface according to the distribution of one of three types of force values - total force, membrane force, or bending force – for all rendered vertices, in a histogram graph that can be dynamically adjusted according to the algorithms described below. This colorization process attempts to render the surface of the thin shell in such a way that it is easy to determine regions of high and low force at a glance, without resorting to the reading of numerical values on the screen. The second view relates to the temporal progression of the animation. With a fixed size buffer cache of all previous frames of the animation, the user has the ability to view the past progression of the current animation, including all vertex locations, force values, force constants, and global parameters, and use this information to analyze the effects of each of these animation parameters over time.

### 4.3.1 Histogram Compression

The histogram compression algorithm attempts to analyze a histogram and adjust the upper and lower ranges so that the force values in the animation are distributed evenly across the entire histogram. This even distribution of values is desirable so that the limited precision of the histograms range segments and the corresponding force coloring are fully utilized. The algorithm pseudo-code is as follows:

```
do {
    boundariesChanged = false;

    /* generate histogram table from current force values*/
    Histogram[] histo = generateHistogramTable();

    /* find segment with many values in lower region of histogram */
    lowerCounter = 0;
    while(lowerCounter < histo.size()) {
        if (histo[lowerCounter].numValues/avgNoOfValuesInSegments > 2.0) {
            break;
        }
        lowerCounter++;
    }

    /* find segment with many values in upper region of histogram */
    upperCounter = histo.size() - 1;
    while ( upperCounter > -1) {
        if (histo[upperCounter].numValues/avgNoOfValuesInSegments > 2.0) {
            break;
        }
        upperCounter--;
    }

    /* avoid compression to range size zero */
    if(lowerCounter == upperCounter) {
        if(upperCounter == histo.size()-1)
            lowerCounter == upperCounter-1;
    }
    else
        upperCounter == lowerCounter+1;

    if(lowerCounter == histo.size()) { } /* no segment found */
    else if( lowerCounter != 0 ) {
        /* segment of interest above lower boundary*/
        histo.minBoundary += 0.5*histo.segmentSize;
        boundariesChanged = true;
    }
    else {
        /* segment of interest at lower boundary */
        histo.minBoundary = histo[0].averageForceValue;
        boundariesChanged = true;
    }
}
```

```

    if(upperCounter == -1) { } /* no segment found */
    else if(upperCounter!= histo.size()-1 ) {
        /* segment of interest below upper boundary*/
        histo.maxBoundary -= 0.5*histo.segmentSize;
        boundariesChanged = true;
    }
    else {
        /* segment of interest at upper boundary */
        histo.minBoundary = histo[histo.size()-1].averageForceValue;
        boundariesChanged = true;
    }
}while(boundariesChanged && !oscillationOccuring());

```

The algorithm effectively expands the range if the edge segments contain many values, and slowly compresses the total range if segments within the histogram have excessive numbers of values within them. The boundary value compression occurs in half segment increments, because the entire histogram distribution changes upon each alteration of the boundary ranges, and even a small change could push many of the values outward towards the boundary segments. Expansion occurs by widening the range boundaries to the average value in the segments on either end of the histogram.

Because we chose to analyze only the resulting histogram table segments and their total value counts at each iteration, our algorithm is simple and fast, but limited in precision. The algorithm does not necessarily converge on an ideal range size due to the fact that the compression process has a fixed precision of one half of an increment. In addition, the expansion process only moves outward to the average of the values in the edge range segments, which is not guaranteed to be beneficial for the histogram to reach its ideal balanced state. As a result of this imprecision in making boundary expansion or compression changes, there is a chance that the algorithm will oscillate the movement of its range values infinitely about an ideal location. To prevent this, the ITS environment implements an oscillation buffer that records the last 50 iterations of boundary value

adjustments. If the average change recorded in this buffer approaches zero for both the upper and lower boundary, then oscillation is detected and the algorithm is stopped.

Figure 5 shows a diagram of the compression and expansion process, and the middle frame of Figure 15 in Section 5.4 shows the visual result of this technique on a thin shell mesh. The mesh in Figure 15 initially exhibits a very small range of force magnitudes on all vertices. The application of the compression process results in a range that reveals the regions of relatively high force, close to the pinned vertex in the top of the screen. The weakness of this algorithm is that in situations where two segments with large numbers border an inner empty region, the final optimized distribution may still be largely uneven. Described in the following section, histogram equalization has the ability to correct for this type of uneven distribution, at the expense of uniformly sized histogram range segments.

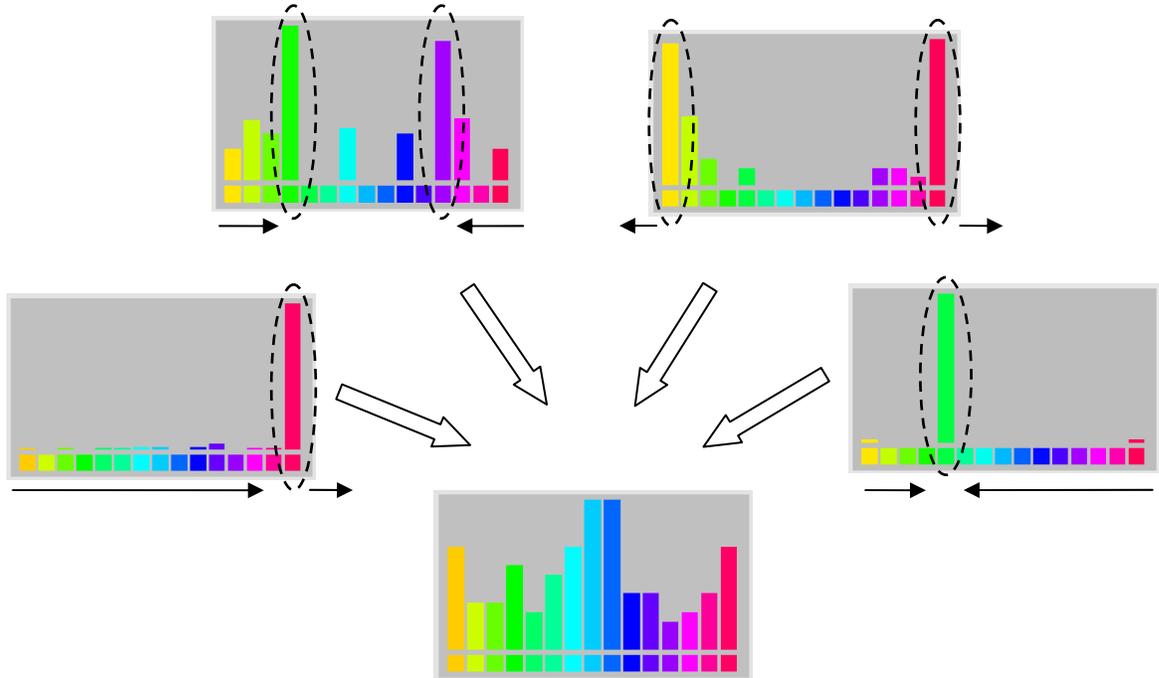


Figure 5 - The ITS histogram compression algorithm.

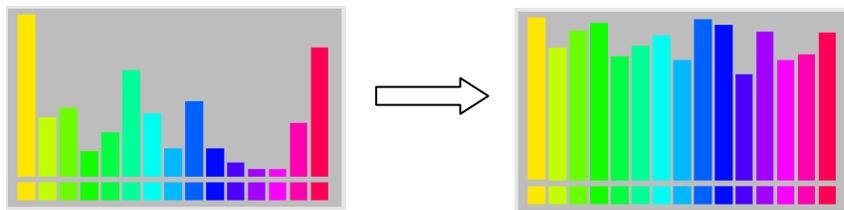
### 4.3.2 Histogram Equalization

Like the histogram compression algorithm, histogram equalization attempts to evenly distribute force values across the entire histogram, to allow for utilization of the full discretized color spectrum for comparative force analysis. However, histogram equalization performs a nonlinear transform on force values based on the cumulative probability distribution of those values, resulting in an effectively non-uniform arrangement of range segment sizes. The benefit of equalization is its ability to distribute any histogram range evenly. The resulting color values reveal difference in range values, but the ranges themselves represent varying size segments, and accurate relative comparisons across range segments in the same image cannot be made easily. Therefore

equalization serves to more effectively optimize the use of the histogram and its range of color, at the expense of accurate force value comparisons.

The histogram equalization algorithm is based on previous work in image processing, and the theory behind its continuous and discrete formations can be found elsewhere [8].

Figure 6 shows the discrete equation that is used in the ITS implementation of histogram equalization. In the equation,  $D_A$  represents an arbitrary force value,  $D_M$  is the number of color levels in the histogram,  $n_k$  is the number of values at force value  $k$  or less, and  $N$  is the total number of force values in the data set. The rightmost frame of Figure 15 in Section 5.4 displays the beneficial results of this process. While the compression algorithm can only tighten the histogram range a limited amount, the equalization algorithm is able to visually enhance the variation in the vertices in the lower region of the screen by equalizing the use of the histogram range and therefore increasing force variation visibility.



$$f(D_A) = \max(0, \text{round}[D_M * (n_k / N^2)] - 1)$$

**Figure 6 - Histogram Equalization**

### **4.3.3 Animation Cache**

The cache of data that stores the history of the current animation can be accessed directly from the main ITS user interface. The cache is a fixed size buffer. If it is filled, the current frame information overwrites the oldest frame information, and the boundaries of the buffer are updated internally. The main user interface presents an interface to the animation cache as a slider bar and a series of buttons that control navigation through the cache data. The slider represents the current information in the buffer, and the rightmost position on it is always the latest cache data. To achieve this translation from a graphical element to an internal data structure, the ITS program must convert the requested progress percentage across the slider bar into an index in the internal data structure. This process must take into account the circular nature of the buffer and ensure that all offsets are valid. The main ITS interface has the ability to request the next or previous frame from given a current frame index received from the buffer at an earlier time, or specify any arbitrary buffer location using a percentage value as a request parameter.

### ***4.4 Full Feature List***

The ITS environment is written in C++ and OpenGL, and makes use of the GLUT graphical user interface library [18]. Because there are many features of the ITS environment which are minor in nature, but contribute to the user experience as a whole, we have compiled a list of all the features that are available in the ITS environment, as follows:

- **Animation Features**
  - Implicit integration with the Modified Conjugant Gradient Method
  - Explicit integration
  - Adaptive time step
  - Arbitrary mesh file support
  - Vertex constraints with 1, 2, and 3 degrees of freedom
  - Vertex-sphere and vertex-cube collision detection
- **User-controlled Parameters**
  - Gravitational acceleration
  - Total mesh weight
  - Desired time step size
  - Membrane force constant per experiment
  - Membrane force dampening constant per experiment
  - Bend force constant per experiment
  - Bend force dampening constant per experiment
  - Location and existence of three environment collision objects: two spheres and a cube
  - Camera rotation and translation
- **User Interaction**
  - Playing and pausing of animation
  - Pinning and unpinning of vertices in a paused animation
  - Spring-based interaction with vertices a playing animation
  - Synchronized interaction across all experiments
  - Navigation of simulation cache: play, pause, first frame, last frame, next frame, previous frame
- **Visualization**
  - Simultaneous mesh experiments
  - Membrane force coloring, direction vectors
  - Bend force coloring, direction vectors
  - Total force coloring, direction vectors
  - Large control points on each vertex
  - Adaptive time step size per experiment
  - Histogram force distribution for current frame

- Current histogram force range values
- Optimized compressed histogram range
- Equalized histogram values
- Wire frame rendering
- Visible or invisible environment collision objects

## 5 Results

In this section, we will highlight some of the important features of the ITS environment that allow it to act as a truly free form experimental environment. Many of the features implemented in the ITS environment, such as adaptive time steps, camera view modification, and animation cache navigation, are difficult to demonstrate with still screenshots, but are completely functional in the implementation.

### *5.1 User Interface Overview*

The main ITS user interface is displayed in Figure 7. In this screenshot, a user is interacting with four simultaneous experiments with varying strengths of membrane and bending forces, and has histogram force coloring enabled. When a user loads up the program, he or she uses the buttons in region A of the screen to select the total mesh weight and load an arbitrary mesh. Region B of the image outlines the region of the interface where the user can modify any of the force or dampening parameters for each of the experiments. Region C contains the view controls which can rotate each experiment independently on its own axis, or rotate the entire group of experiments at once. Region D is where the user is able to control the progress of the animation algorithm. In this area, the user can play and pause the animation, reset the experiments and global parameters back to their original initial conditions, or restart the animation system and reload an entirely new mesh for experimentation. Region E outlines the group of global controls which allow the user to alter the gravitational acceleration or time step, enable or disable the displayed cube and sphere environment collision objects, enable or disable the rendering of force vectors to augment the force coloring, and enable or disable wire

frame rendering. Region F houses the controls for the dynamic histogram capabilities in ITS. From this location in the interface, the user can enable force coloring, select the forces to be represented on the screen, and reset, compress, or equalize the histogram for the current frame or all recorded frames. Region G highlights the visual representation of the force histogram, as discussed in Section 4.3. At the bottom, region H outlines the group of controls that allow the user to play back cached animation data, and select any frame of interest for further analysis. Finally, region I marks the visual cues for the current adaptive time step status. Each of these bars represents the size of the current time step for each experiment on screen, in relation to the requested time step indicated in the global preferences panel on the right side of the screen. If the bar is full, then the current step size is equal to the requested step size.

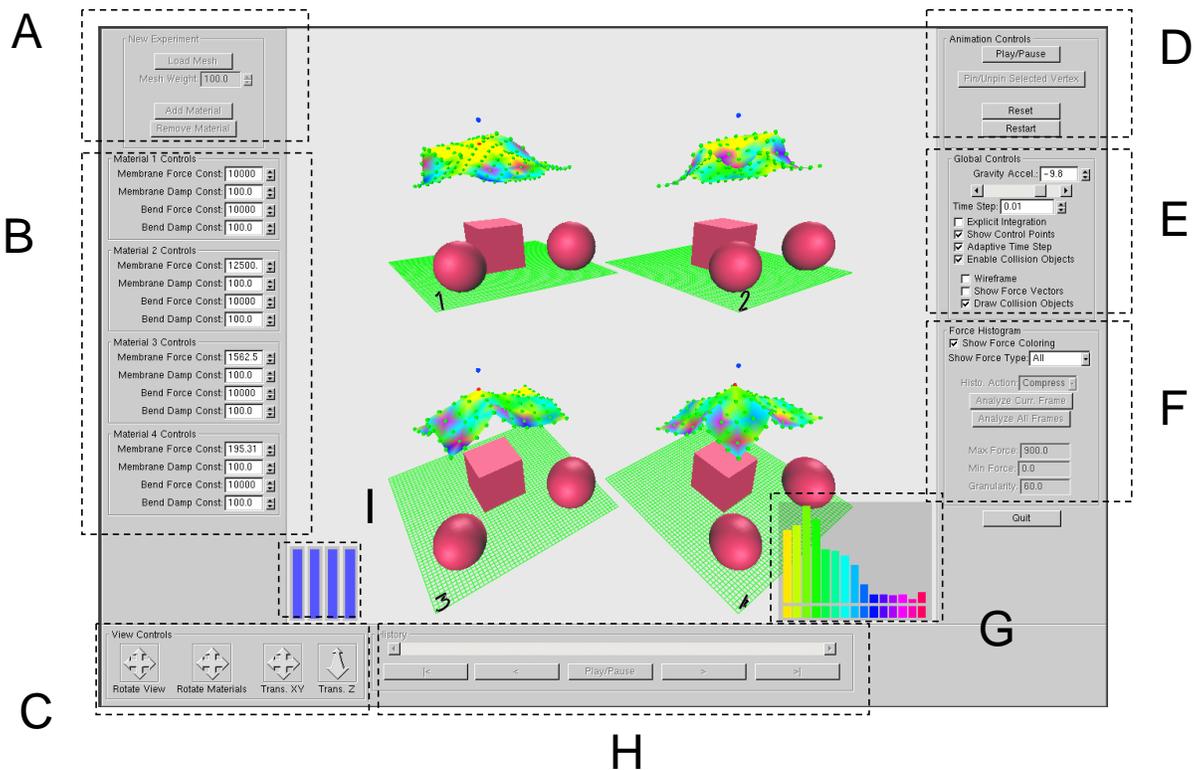
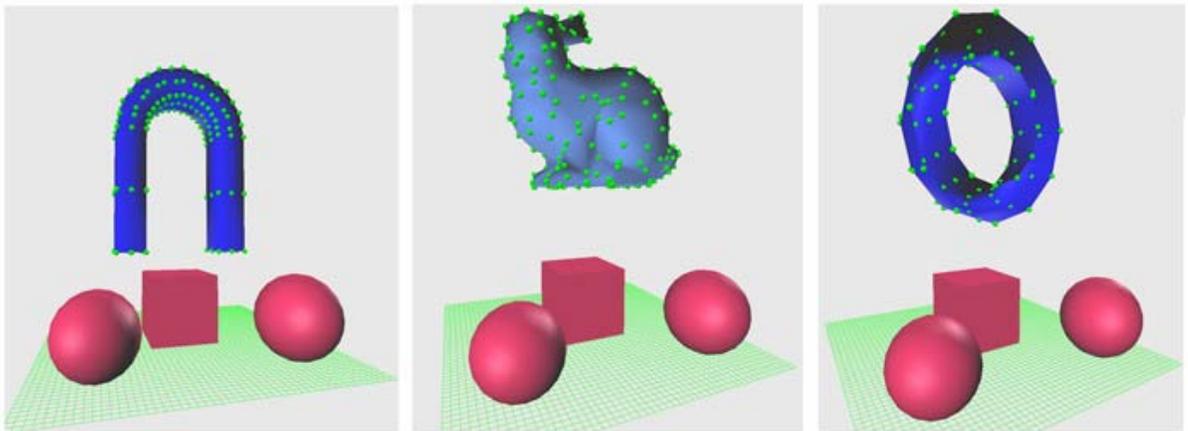


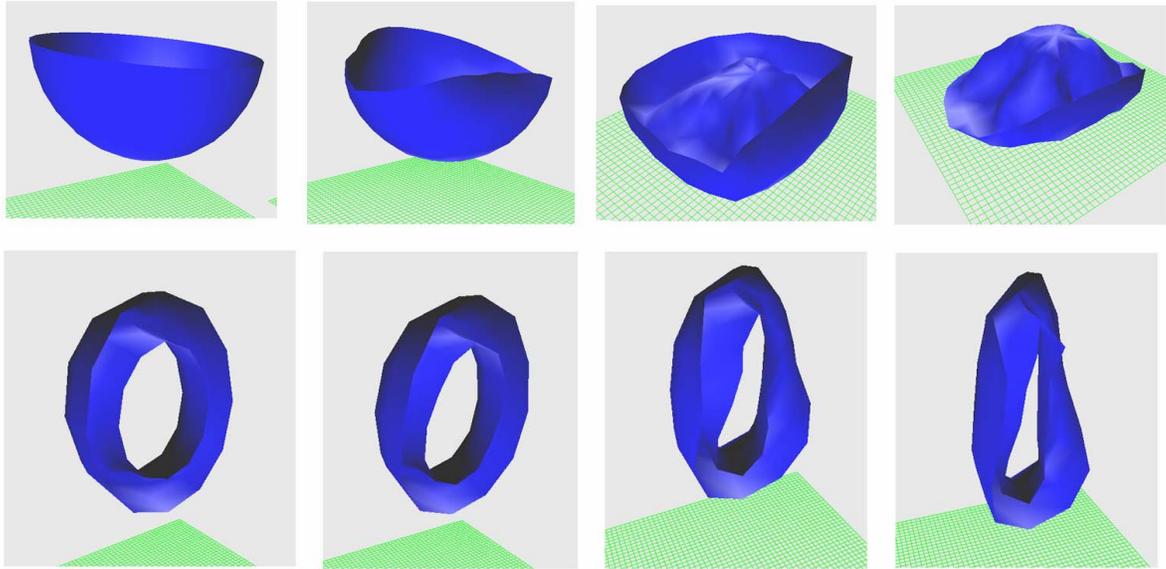
Figure 7 - The ITS Graphical User Interface

## 5.2 Animation Features

While the explicit and implicit integration capabilities are fully functional, screenshots would not help to convey the results of the implementation. As expected, the explicit mode requires an extremely small adaptive time step, on the order of 0.00001 seconds,  $1/100^{\text{th}}$  the size of the implicit mode time step, in order to keep the animation stable with high membrane and bending force coefficients. Figure 8 shows the loading of various arbitrary mesh files. The classic bunny model in the middle has no color assignment embedded in its mesh file, so it is rendered with a default powder blue coloring. In this screenshot, the green dots represent the locations of vertices on the model, and also serve as a representation of the control points of user interaction during live and paused animation states. Figure 9 demonstrates a set of simultaneous experiments with varying membrane and bending force constants. Each displayed experiment is shown at the same moment in time, and demonstrates varying reactions to collisions or pinned vertex constraints.

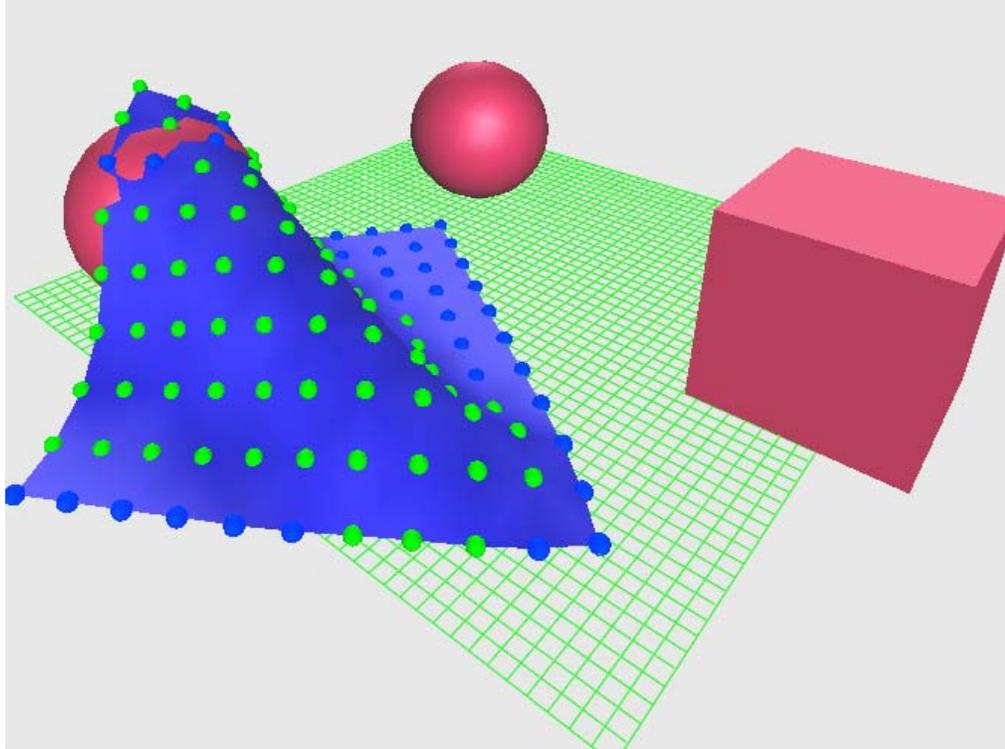


**Figure 8 - ITS supports arbitrary mesh files.**



**Figure 9 - Two mesh experiments. A hollow half sphere impacting an invisible cube, and a hanging hollow half torus are shown at the same moment in time, with decreasing membrane and bending force constants, from left to right,  $k_b=k_m=100000, 12500, 1562, 195$ .**

In Figure 10, both constraints and environment object collisions are shown to be functioning correctly. The portion of the sphere appearing through the blue sheet is due to the fact that we implemented simple vertex-sphere and vertex-cube intersection testing, and did not analyze triangle face intersections, since it was not an essential part of this project. The control points that appear blue in this Figure represent vertices which have been constrained in some manner. The vertices in contact with the sphere have been constrained along the vector that points from the center of sphere to their current location, and the constrained vertices on the ground are constrained along the y-axis.

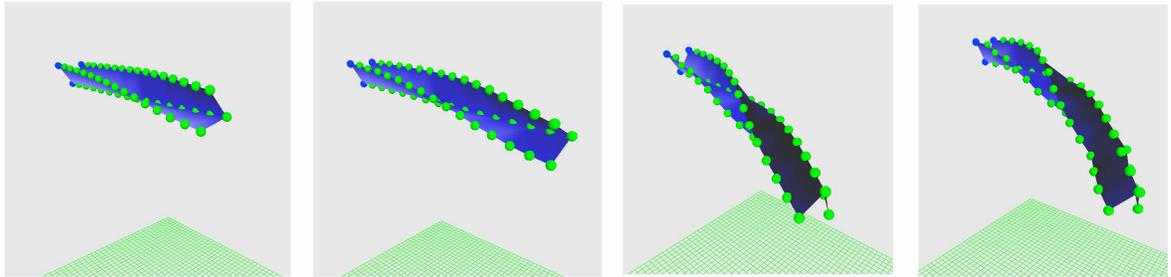


**Figure 10 - ITS supports simple vertex collision with the environment. Blue control points represent constrained vertices.**

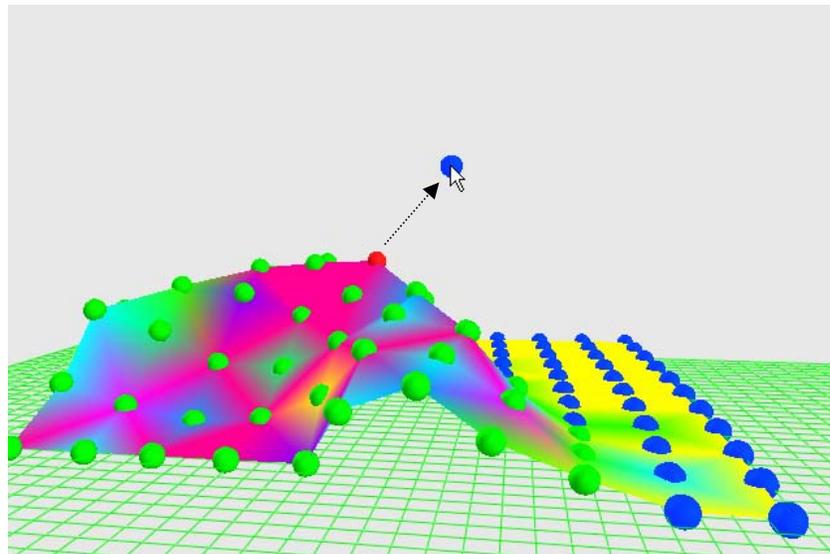
### ***5.3 User Interaction***

The screenshots in Figures 11 and 12 demonstrate the paused and live interaction modes, respectively. The v-beam in Figure 11 has one end pinned, while the rest of the mesh is left to succumb to gravity. Each displayed mesh has a varying level of bending force, and is shown at the same moment in time. As is expected, the v-beam loses its structural rigidity when its bending energy is reduced. Figure 12 demonstrates live user interaction using a spring force. Here, the user has selected the vertex colored by a red control point, and is dragging the cursor over the location of the blue control point, which represents the

target constraint location. In addition, force coloring is enabled in this image, revealing the redder regions of high force at the point of user interaction.



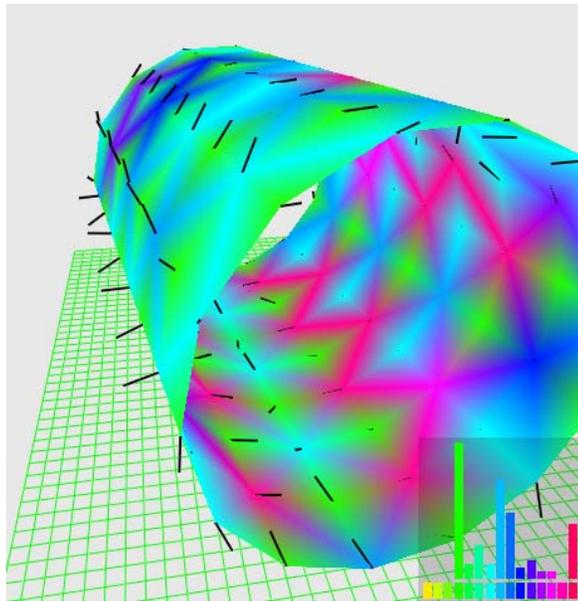
**Figure 11 - A simultaneous experiment with pinned v-beams with varying decreasing bending forces from left to right,  $k_b=100000, 12500, 1562, 195$ .**



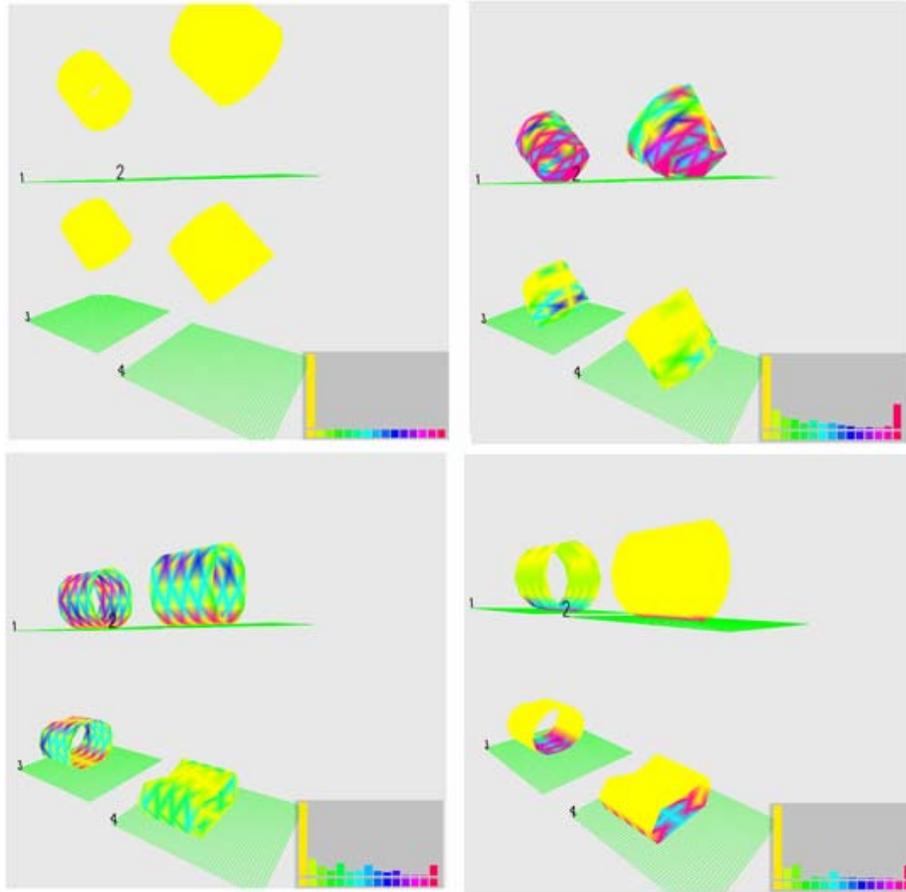
**Figure 12 - Live Interaction. When a user clicks and drags a vertex, a linear constraint force is applied to the selected vertex towards a world coordinate determined by the mouse. The arrow on the screenshot shows the direction of the force.**

## 5.4 Visualization

In the screenshot in Figure 13, a hollow cylinder lies flat on the floor, and its surface is colored according to the histogram coloring scheme. Force vectors are also visible on its surface, which augment the coloring by indicating the direction of the force currently being viewed. Similarly, Figure 14 shows the progression of force coloring of the duration of an animation. In this example, four simultaneous experiments with a mesh cylinder of varying membrane and bend constants are analyzed, with membrane forces only enabled in the upper left, upper right, and lower left frame, and total forces rendered in the lower right frame. The final frame demonstrates the membrane energies canceling out the gravitational force on the top of the cylinder, and residual vibration between the floor boundary and the bottom of the cylinder introducing a small amount of force on the lower side of the object.



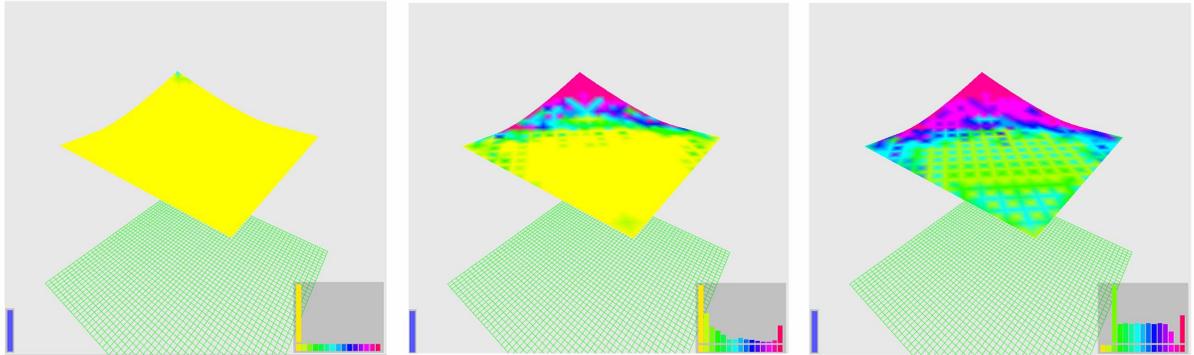
**Figure 13 - Visible force vectors and vertex coloring**



**Figure 14 - The progression of forces in four dropped cylinders with varying internal force contributions. Shown are the initial conditions (top left), two steps of internal force progression (top right and bottom left), and final total force magnitudes (bottom right).**

The histogram compression and equalization algorithms are displayed in action in Figure 15. The plane mesh in this screenshot is pinned at one vertex in the upper area of the screen. Initially, that default static force distribution is insufficient for revealing the force variations on the mesh at this stage in the animation, as displayed in the leftmost frame. In the middle frame, the compression algorithm has altered the range as much as it could while maintaining fixed size range segments. In this state, the image has a larger contrast and the variations in the forces across the upper region of the mesh are more apparent, but much of the lower region shows very little visual variation. In the rightmost frame of

this figure, the equalization algorithm properly distributes the force values across the histogram, at the expense of fixed color range segment sizes. In this final stage, the force variations are very visible, but judgments about their relative force intensities would be inaccurate, due the nonlinear force value mapping.

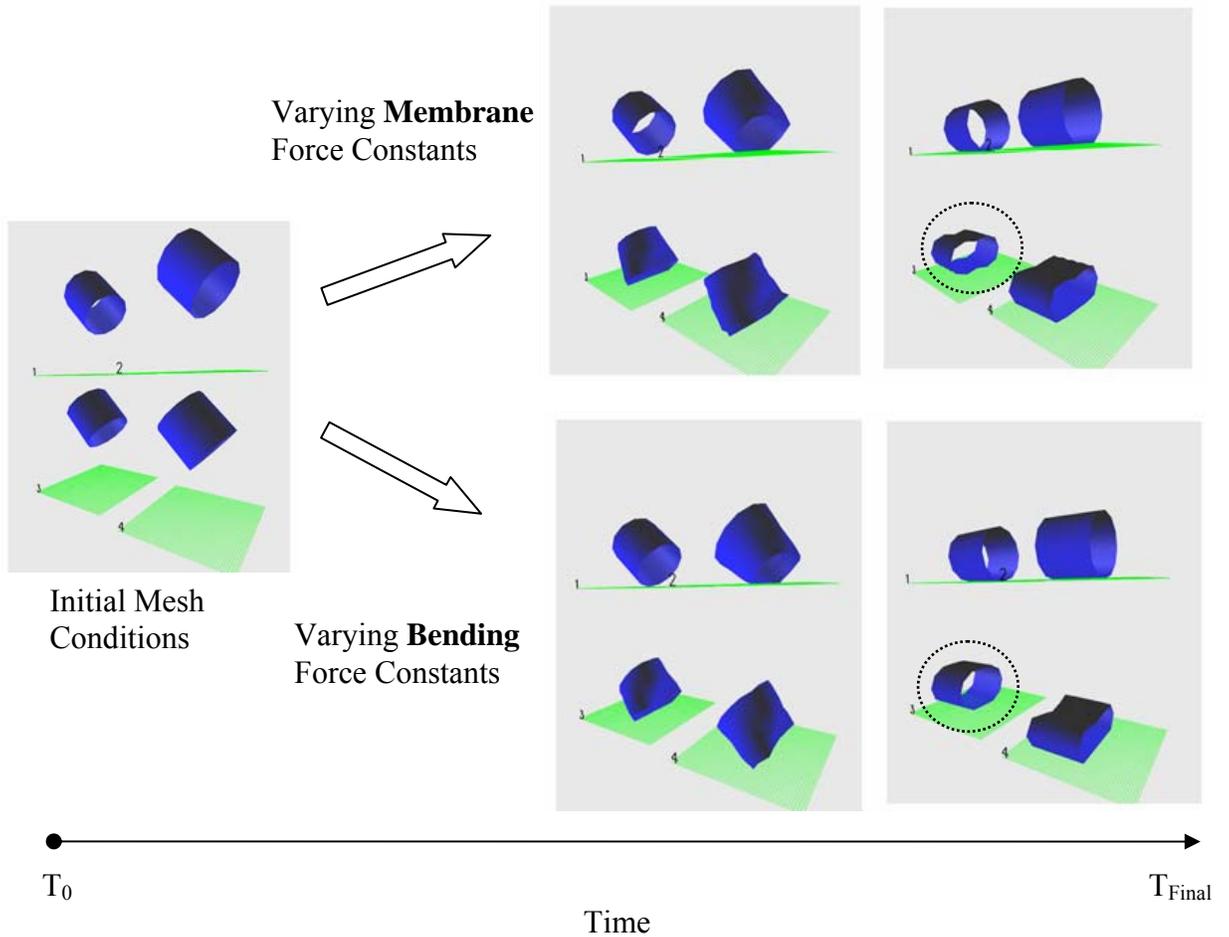


**Figure 15 - Histogram Compression and Equalization. The original histogram range (left), the compressed range (middle), and the compressed and equalized range (right).**

### ***5.5 Thin Shell Model Weaknesses***

During some of the testing performed on both the ITS interface and the underlying physically based animation, we observed directly the weaknesses in our bending force approximation. As discussed in Section 4.1.2, the bending forces in our physical model are simple linear constraints across the shared edge of two triangles. Given a rest condition in which the angle between a pair of triangles is close to 180 degrees, any bending that occurs will not be resisted strongly until the bending angle has extended far from that nearly flat configuration. This occurs because the linear bending constraints are nearly parallel to the pair of triangles, and imbue little force along the normal of each of the triangles in question until a large amount of deformation occurs. This becomes extremely obvious in the simultaneous experiments performed in Figure 16. In this

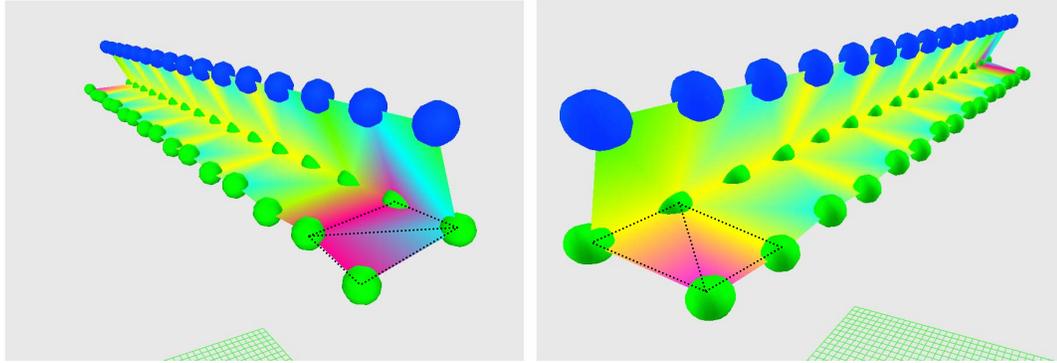
Figure, two sets of experiments are run. In the upper set, the bending constraints were kept equal and the membrane forces were decrease in order of left to right and top to bottom. In the lower set, the membrane force constraints are kept constant, and bending forces are reduced. Given equal bending force constants, the upper set of panels shows that when the membrane force is low, the bending force is the primary source of structural integrity. When this occurs, the bending force cannot withstand the gravitational force on the top of the cylinder, and the faces along the top invert their angle. This occurs because the initial configuration of the cylinder generates bending constraints that are all nearly 180 degrees, and therefore weak until significant deformation occurs. In the bottom set of panels, the membrane force is equal amongst all experiments, and prevents the angle inversion from occurring, showing that the bending force in the cylinder model contributes very little in these experiments, due to the high angles between all the faces of the mesh.



**Figure 16 - The progression of two animation runs. The circled mesh reveals a weakness in our thin shell approximation.**

Another inherent weakness was found in our algorithm that stems from its discrete nature. This weakness is not unique to our implementation, but extends to any physically based animation model that relies on a discrete geometric formulation of an object to determine the dynamics involved. Figure 17 demonstrates this weakness. The screenshot shows a v-beam constrained on an entire side and left to hang under the force of gravity. While, in the middle of the mesh, the bending and membrane forces are countering gravity equally, the corner vertices have less support from neighboring geometry and thus

gravity is countered in weaker manner, resulting in higher force magnitudes in these locations. However, both corners do not exhibit expected symmetric force distributions, due to the discrete triangulation of the mesh. This structure results in one corner vertex that has three membrane constraints to neighboring vertices, as seen on the right frame of Figure 17, while the other corner vertex in the left frame has connections with two neighboring membrane constraints and a single, weaker bending constraint across to the neighboring triangle. Therefore, the inherent discrete geometry of the model prevents it from accurately mimicking the symmetric forces that would have resulted from a similar real world experiment with a thin shell material in a similar configuration. In order to more fully replicate the real world, this algorithm would require a more complex, continuous underlying mathematical model independent of any discrete approximations. This same figure also further reveals our weak bending force approximate in the alternating vertex colors, and therefore vertex force values, that occur along the middle of the v-beam. Ideally, all the middle vertices should have an identical bending force magnitude, because they are experiencing the same gravitational pull, but due to our linear constraint approximation, the flat edge angles along the top and bottom flap of the mesh are contributing much weaker force vectors compared to the high angle bending constraints that occur on every other vertex, each of which is part of a triangle that shares an edge with another triangle across the sharp acute angle in the model.



**Figure 17 - Unrealistic Forces.** Two panels (left, right) show bending force views of two sides of the same experiment on a v-beam with pinned vertices. The forces are asymmetric due to the underlying triangulation of the mesh. The black lines indicate triangle edges.

## ***5.6 Performance***

The ITS environment uses a large amount of memory to store animation cache data, and performs a large number of mathematical operations per iteration, resulting in a simulation that has some very obvious performance weaknesses. On our test system, which is an Athlon 64 3500+, with 1 GB RAM, and an ATI Radeon X850XT graphics card, the simulation became unusable, with non-interactive frame rates, at approximately 1200 vertices on screen at once. Our tests were performed with a 1300 frame cache. Each frame of data occupies approximately 125 bytes per vertex. In terms of memory usage, with the establish 1300 frame cache, one gigabyte of memory will be occupied by purely frame data when approximately 6614 vertices are rendered on screen at once. According to these calculations, the simulation on our test machine is primarily limited by its calculation speed, as opposed to its memory footprint. These testing results are limited to a single computer and therefore are useful only for grasping a general idea of the level of performance that is achieved with this application. Due to the fact that the ITS

environment and its thin shell model were constructed to demonstrate a unique tool with no known comparable implementations, it was not constructed with optimization and competitive performance analysis in mind. In addition, much of the computational limits of the ITS system arise due to the specific implementation of the thin shells model, which is not the core focus of this paper. Because of both of these reasons, there is likely much room for both memory and computation optimization throughout the program.

## 6 Conclusions

The Interactive Thin Shells application we have designed and implemented has fulfilled our ultimate goals for the project, through intentional and unintentional means. Our goals were to construct an application that provides an experimentally-focused, open, informative and very accessible interface to a physically based animation algorithm. With these higher level intentions in mind, we examined related research areas and turned to the more specific requirements of Michael Rooks and his framework for VIS applications [21]. These requirements served as a basic guide for the construction of our simulation. In Figure 18 below, we compare these requirements to the final implementation of our system. Ultimately, we satisfied each one of these requirements in multiple ways, so that the user has a large array of useful visual information available to them.

<b>Rooks' VIS Requirements [21]</b>	<b>Interactive Thin Shells</b>
1 Intervention	<ul style="list-style-type: none"> <li>▪ Vertex pinning/unpinning</li> <li>▪ Mouse-activated constraint force</li> <li>▪ Animation play/pause/reset</li> <li>▪ Collision object enabling/disabling/movement</li> </ul>
2 Inspection	<ul style="list-style-type: none"> <li>▪ Cache of vertex locations, experiment and global parameters</li> <li>▪ Displayed histogram range values</li> <li>▪ Displayed adaptive time step values</li> <li>▪ Displayed experiment and global parameters</li> </ul>
3 Specification	<ul style="list-style-type: none"> <li>▪ User-defined mesh weight, force constants, dampening constants, gravity, time step</li> </ul>
4 Visualization	<ul style="list-style-type: none"> <li>▪ Shaded rendering</li> <li>▪ Force histogram coloring</li> <li>▪ Wire frame rendering</li> <li>▪ Force vector rendering</li> </ul>

**Figure 18 - A comparison of VIS requirements and the ITS implementation**

Beyond simply matching features of our software to a set of established requirements, the ITS program performed its task well enough that we were able to unintentionally use it to identify substantial weaknesses in the chosen thin shell model. While the bending angle constraint simplification was known to be imperfect, the subtle behavior of weak bending forces at extremely obtuse angles and their results on the animation as a whole were only obvious after we completed and replayed simultaneous experiments on multiple meshes while varying specific parameters. In addition, the force coloring patterns in specific pinned mesh configurations were another clear indicator that reinforced the notion that our simplistic bending force was not a completely adequate model in many cases. The additional discovery of asymmetric forces that resulted directly from the discrete triangulation of a mesh was another phenomenon that was found only after close inspection with the ITS interface. In this case, the histogram compression algorithm was essential in allowing us to perceive the force asymmetry in the v-beam mesh in Figure 17. Due to the fact that many physically based animations represent real world objects with discrete approximations, such as triangles meshes, the ability to discover and analyze the flaws in these approximations is an extremely valuable feature of the ITS interface, and further exhibits the usefulness of the tool in situations outside of thin shell animation.

Our software has therefore shown itself to fulfill a set of established requirements for interactive computer simulations, as well as serve as a tool in discovering and analyzing both a flawed algorithm and an inaccurate object representation. It therefore has promise as a fundamentally useful tool for computer science students and professionals interested in the complex workings of modern physically based animations. It is our hope that the

interface features of the ITS system will help to guide the development of similar interactive interfaces for more complex physically based models. There is no doubt there are a large number of animation algorithms in existence that could benefit from a more tactile and experimental interface which can help to clear the muddled waters of abstract mathematics and help bring it into the light of intuitive experience.

## 7 Future Work

The ITS interface can be further developed in a number of ways. The most important optimization would include more efficient storage of simulation cache data through data packing or compression. The cache capabilities could also be extended to support buffering to hard disk when dealing with very large meshes or very long animation runs. In addition, further cache improvements may involve the support the progression of animation calculations from a past point in time. This action would erase any existing information in front of the selected cache buffer location, and allow a user to recalculate past animation events with new experiment parameters. With this enhancement, the cache size would be increased to store past collision and constraint information, but ultimately enable more flexible control of the animation as a whole. The current iteration of our interface does not have the capability of saving the settings and cache generated during an experiment. Future work would involve implementing a saving and loading system that stores and loads the mesh data, cache data, and other settings together in some unified manner, so that a user can save the data generated by the ITS interface for later review and analysis. The force coloring scheme could also be improved by implementing a form of surface shading that does not excessively obscure the surface coloring, yet preserves the visual depth that is often lacking in our current implementation. To make the ITS program a more useful and widely accepted design, the user interface, histogram, and caching mechanism could also be constructed to access a standard API which would connect to a set of animation “plug-ins” that contain complex animation code. These pieces of software could partially customize the ITS interface for their specific algorithm

parameters. In this way, the ITS design would be a truly generalized and accessible interface for a large assortment of mathematically intensive animation models. The underlying thin shells simulation itself can also be greatly improved. Primarily, it would benefit from more optimization time. Many of the underlying matrix and vector mathematics could be offloaded to the highly parallel graphics processors so prevalent in home computers today [19]. Furthermore, the thin shells model could be modified to completely implement the more accurate discrete shells model of Grinspun et al [9], and therefore provide a more realistic animation of thin shell materials.

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