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(54) **THREE DIMENSIONAL MODELING AND ANIMATION SYSTEM USING MASTER OBJECTS AND MODIFIERS**

(75) Inventors: **Daniel David Silva**, San Rafael, CA (US); **Rolf Walter Berteig**, Seattle, WA (US); **Donald Lee Brittain**, Santa Barbara, CA (US); **Thomas Dene Hudson**, Port Washington, WI (US); **Gary S. Yost**, San Francisco, CA (US)

(73) Assignee: **Autodesk, Inc.**, San Rafael, CA (US)

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G06T 15/00 (2006.01)

G06T 17/00 (2006.01)

(52) **U.S. Cl.** **345/419**; 345/420; 345/619

(58) **Field of Classification Search** 345/419, 345/619, 441, 645, 427, 650, 661, 676, 473
See application file for complete search history.

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Primary Examiner—Ulka Chauhan

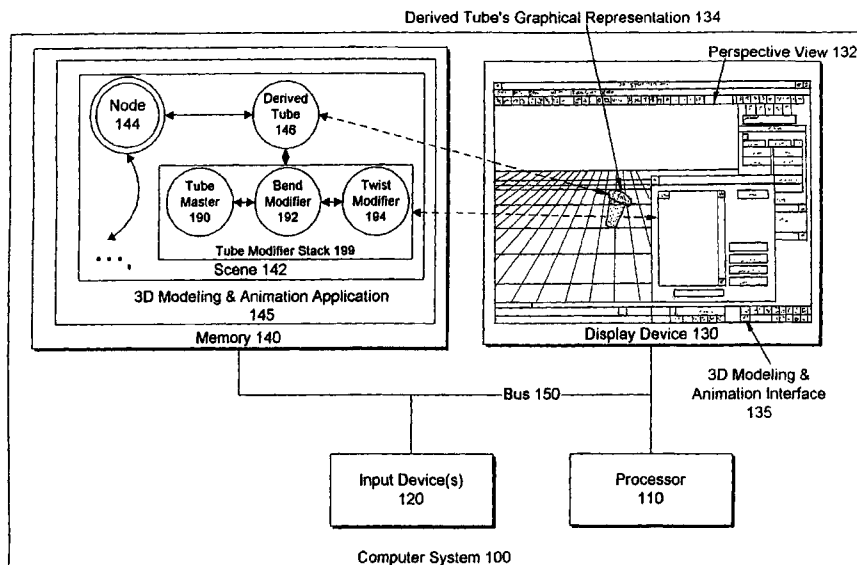
Assistant Examiner—Daniel Hajnik

(74) *Attorney, Agent, or Firm*—Patterson & Sheridan, L.L.P.

(57) **ABSTRACT**

A three dimensional (3D) modeling system for generating a 3D representation of a modeled object on a display device of a computer system. The modeled object is represented by an initial definition of an object and a set of modifiers. Each modifier modifies some portion of the definition of an object that may result in a change in appearance of the object when rendered. The modifiers are ordered so that the first modifier modifies some portion of the initial definition of the object and produces a modified definition. The next modifier modifies the results of the previous modifier. The results of the last modifier are then used in rendering processes to generate the 3D representation. Each modifier is associated with a three dimensional representation so that the user can more easily visualize the effect of the modifier.

8 Claims, 14 Drawing Sheets



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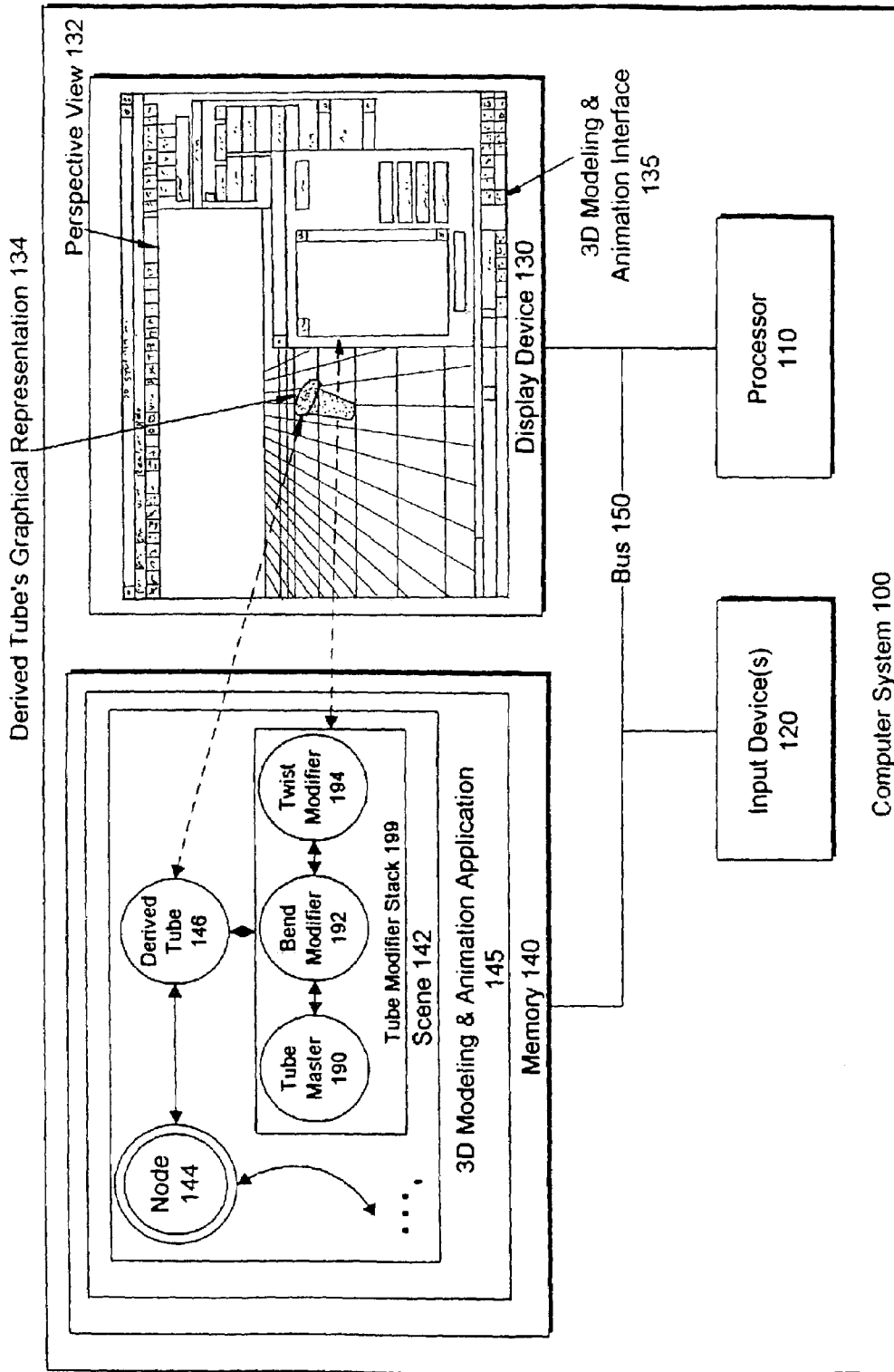


Figure 1

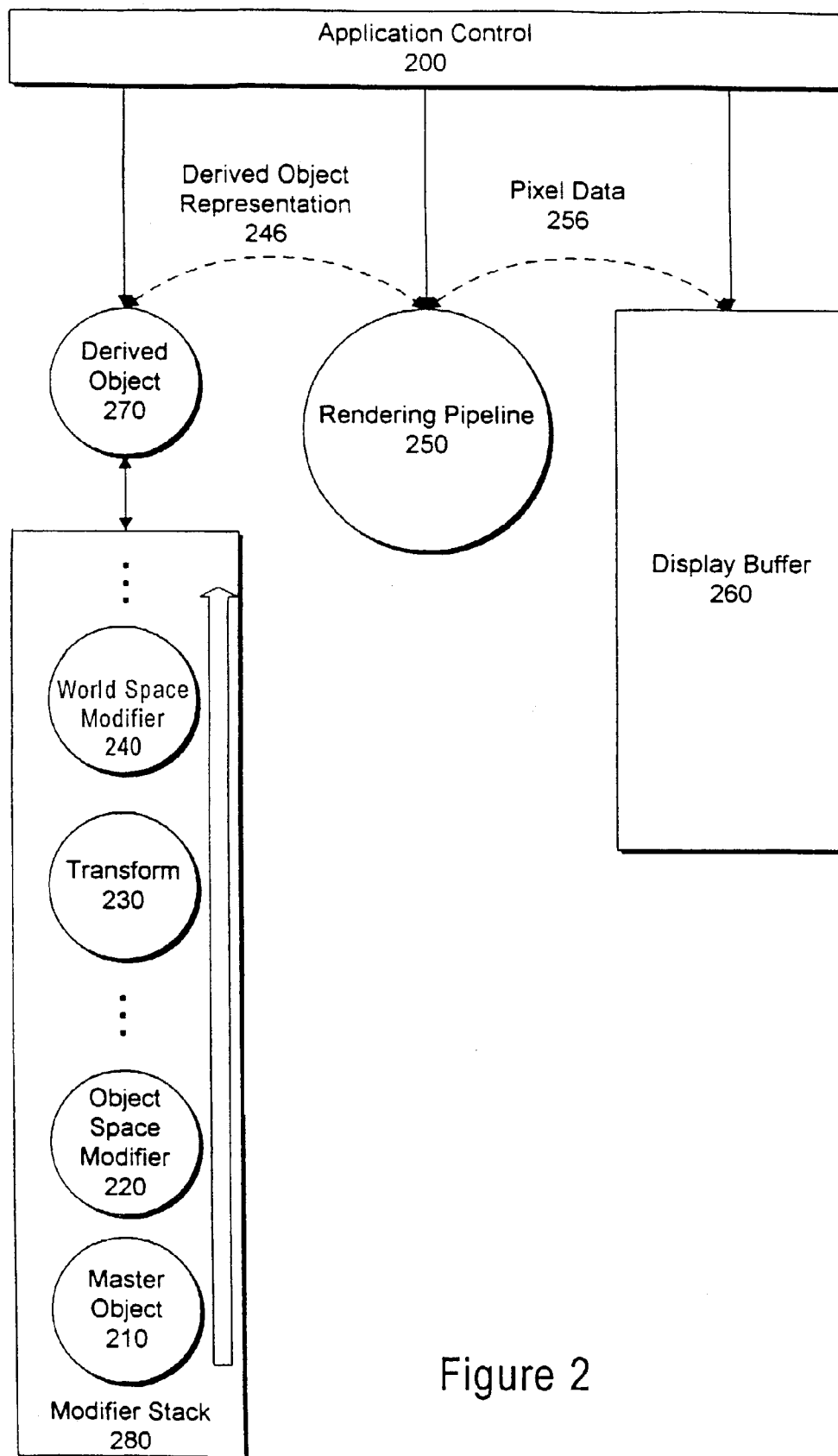


Figure 2

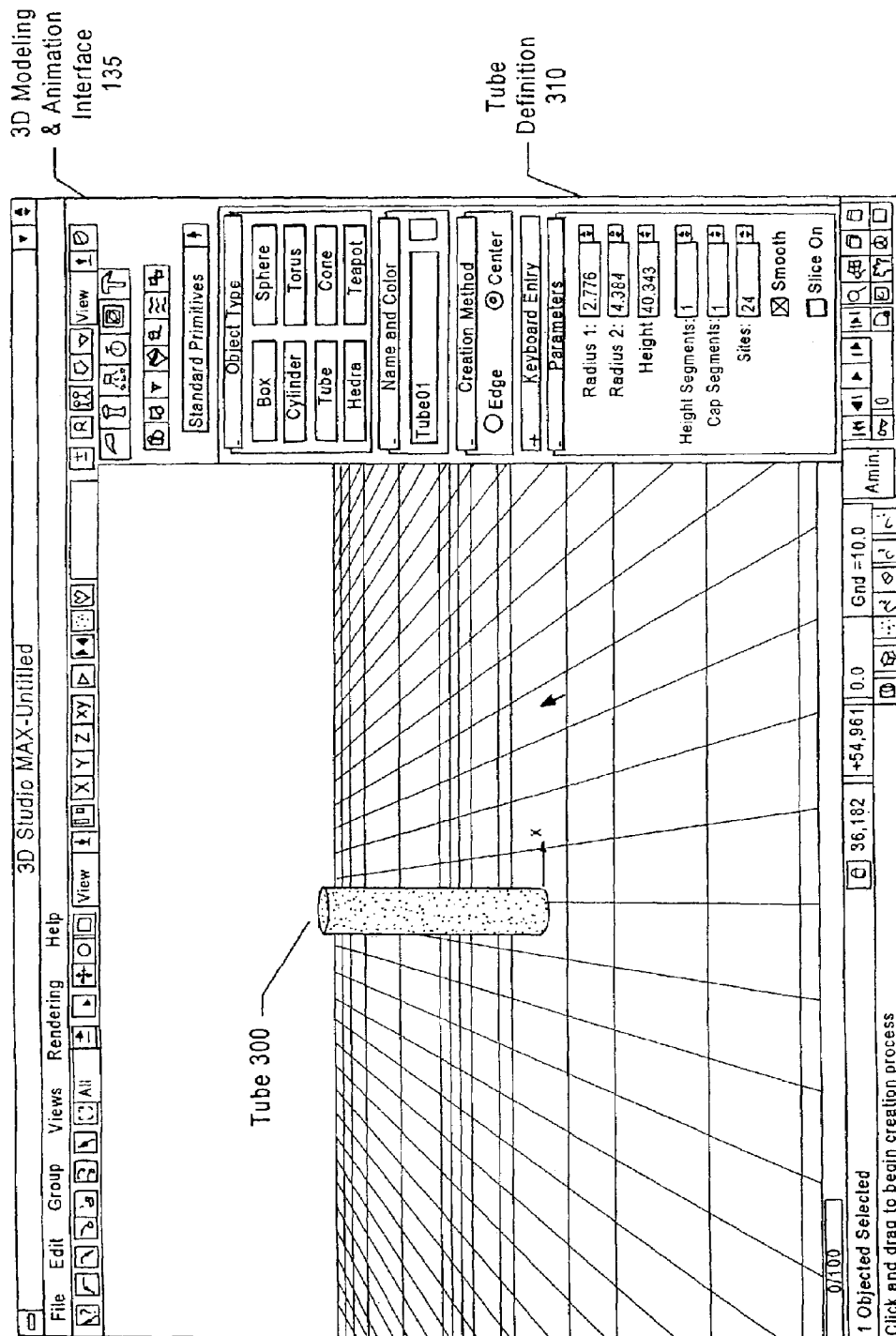


Figure 3

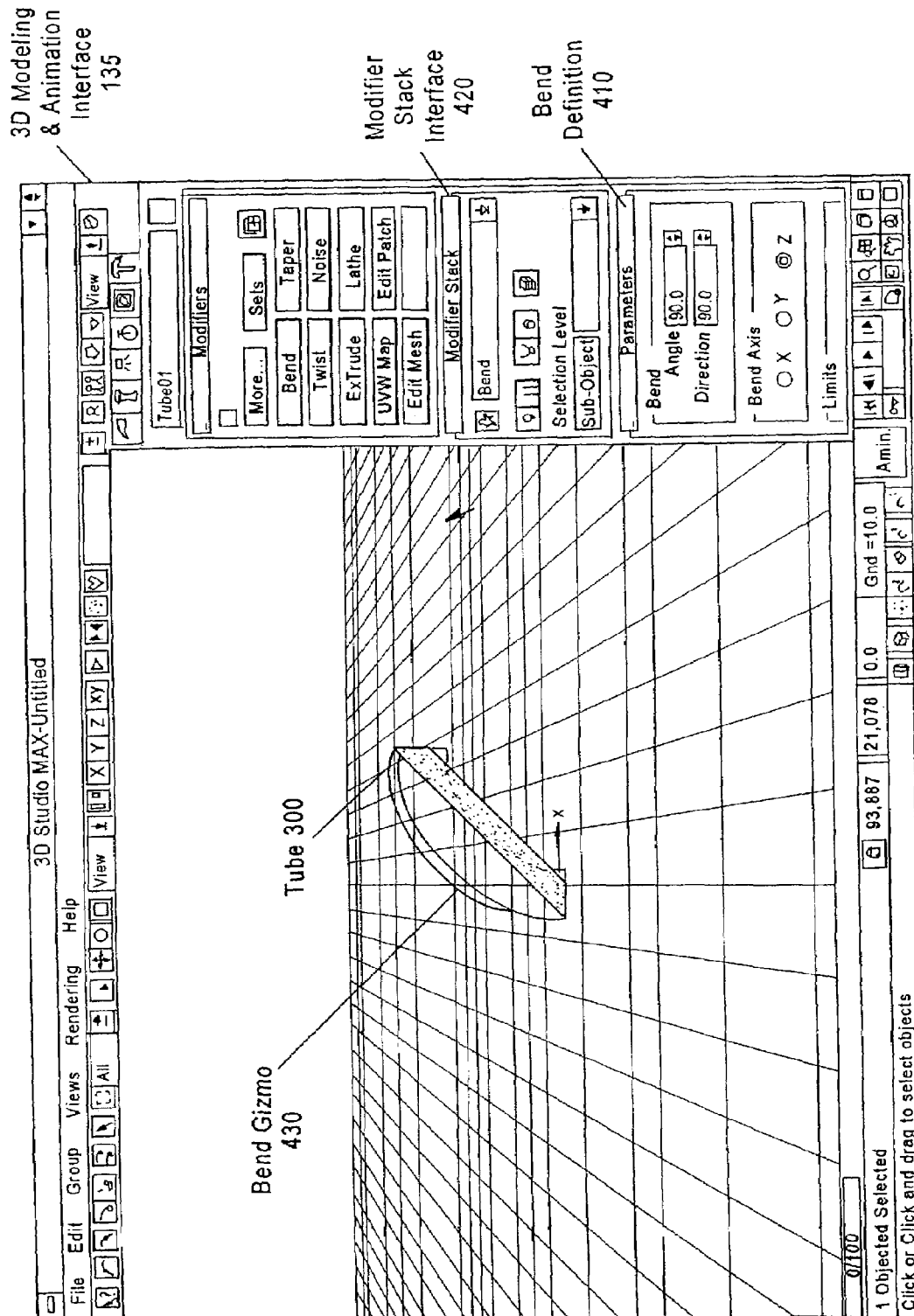


Figure 4

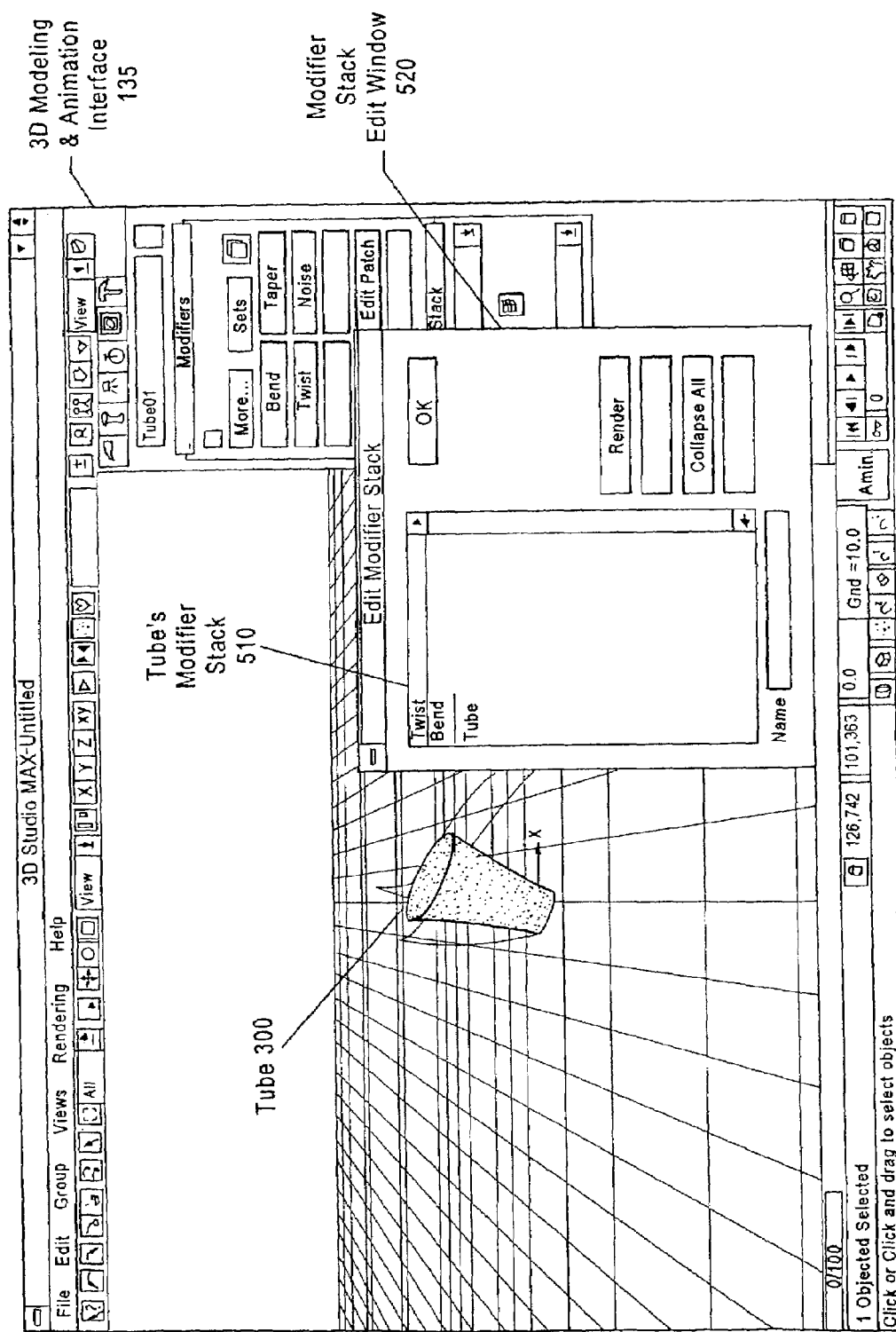


Figure 5

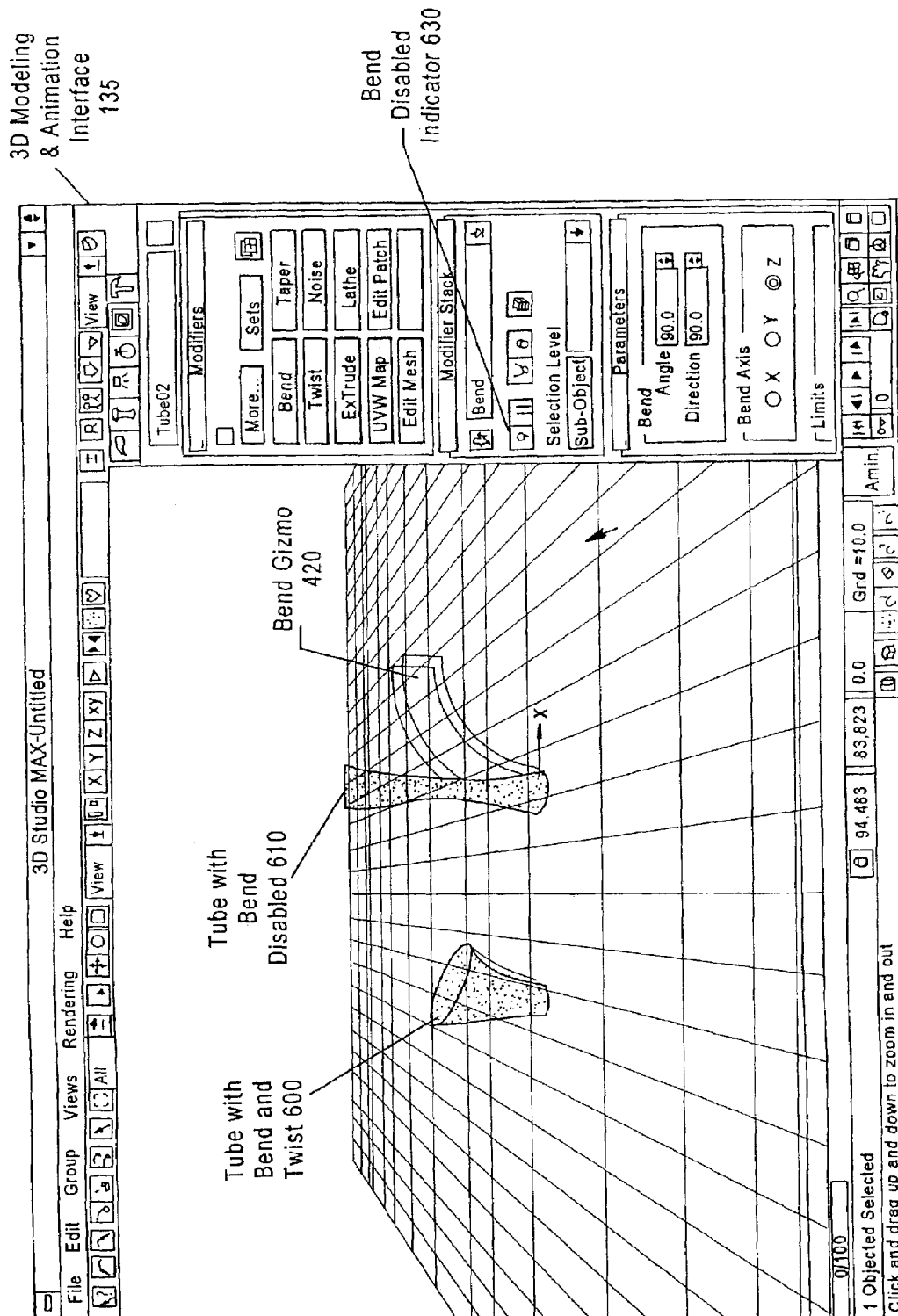


Figure 6

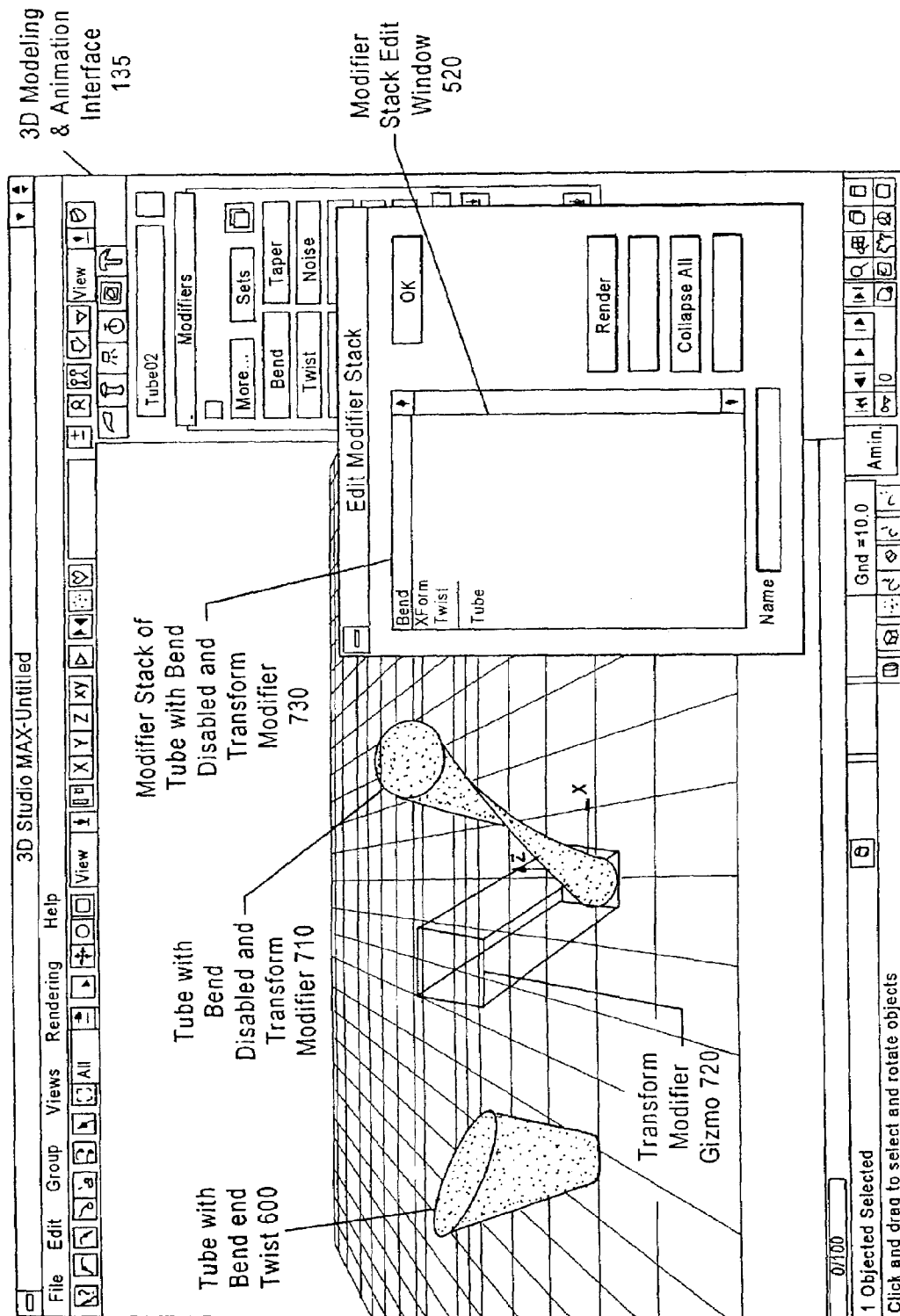


Figure 7

3D Modeling
& Animation
Interface
135

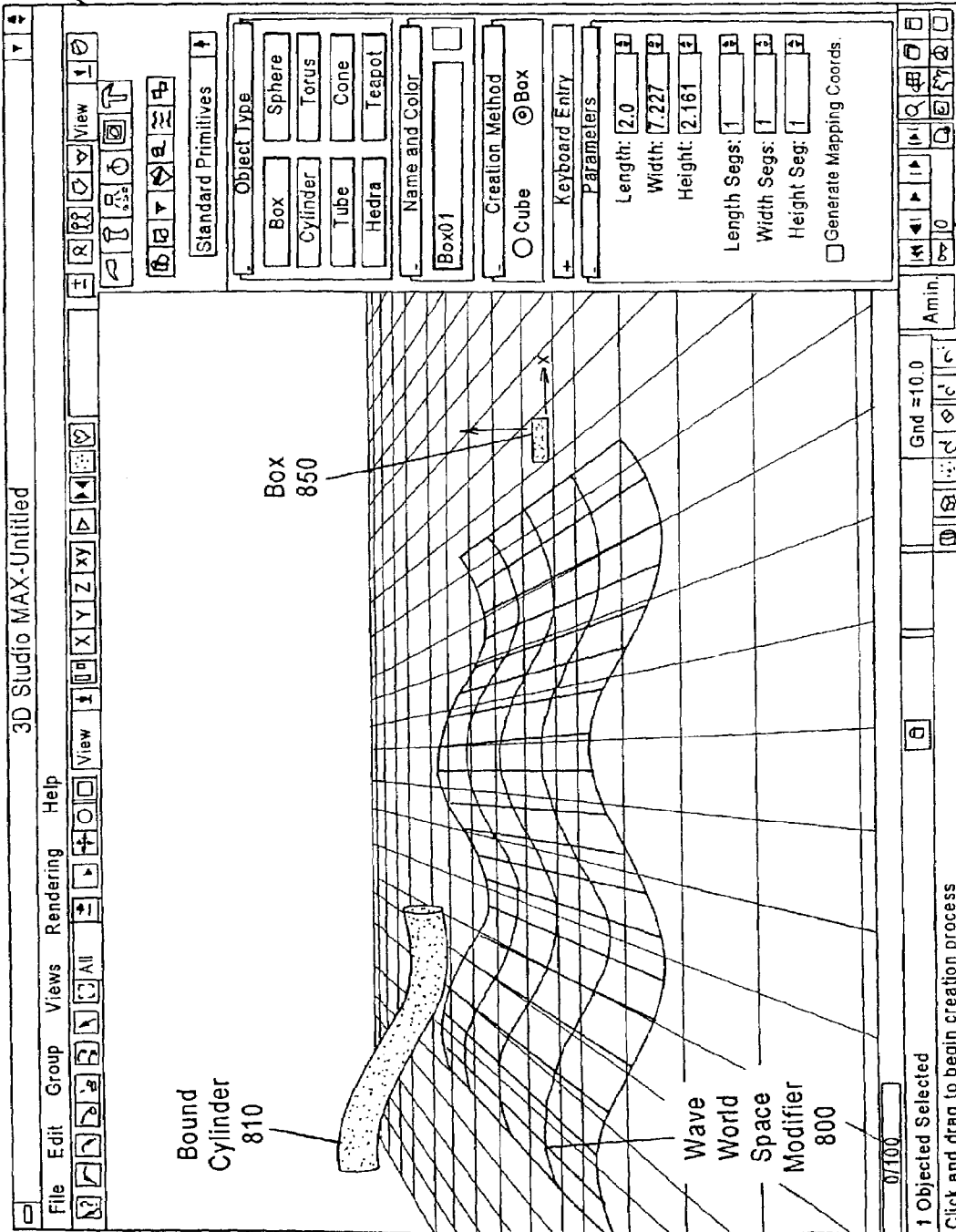


Figure 8
Frame Indicator 840

3D Modeling
& Animation
Interface
135

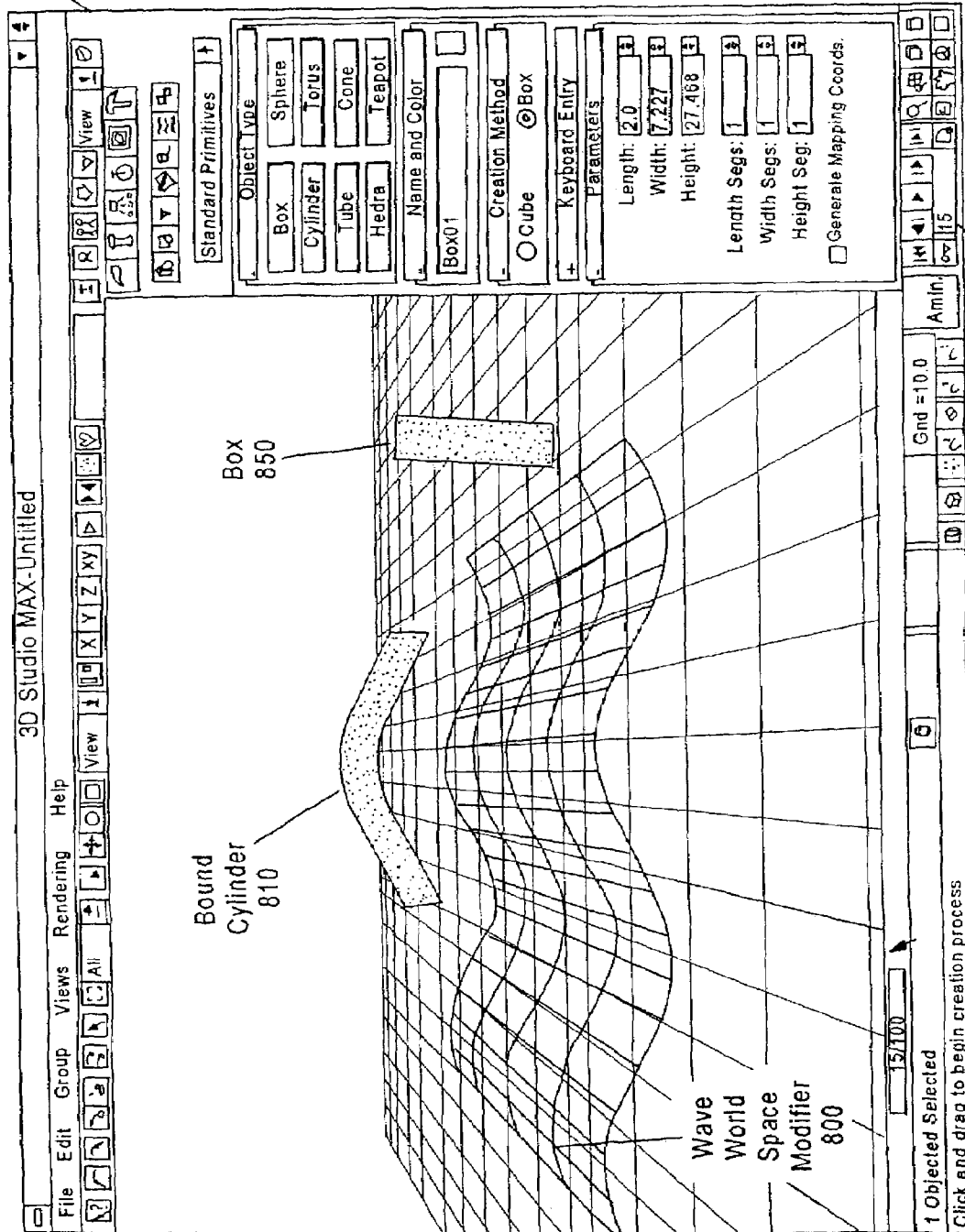


Figure 9

Frame
Indicator
840

3D Modeling
& Animation
Interface
135

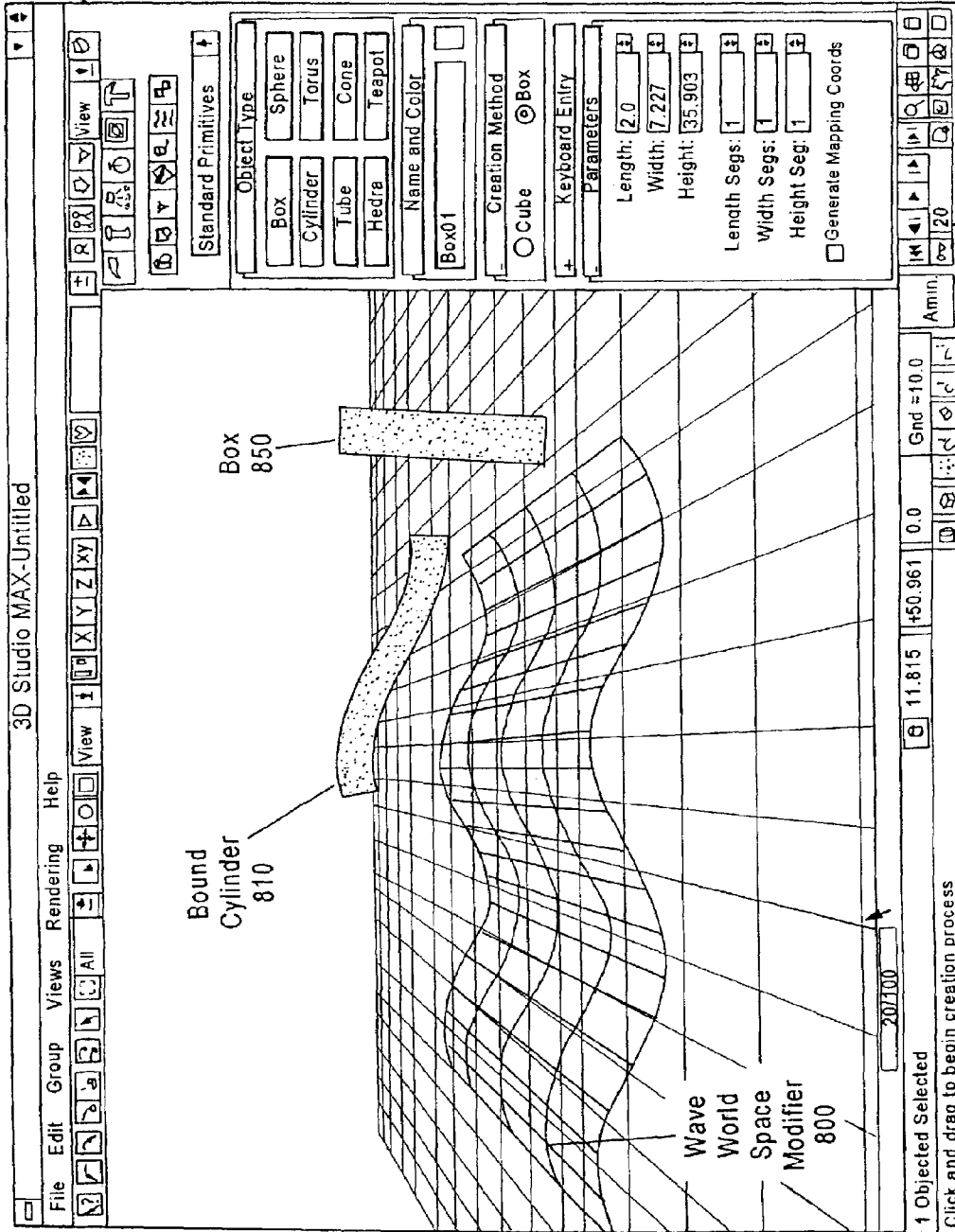


Figure 10

Frame
Indicator
840

3D Modeling
& Animation
Interface
135

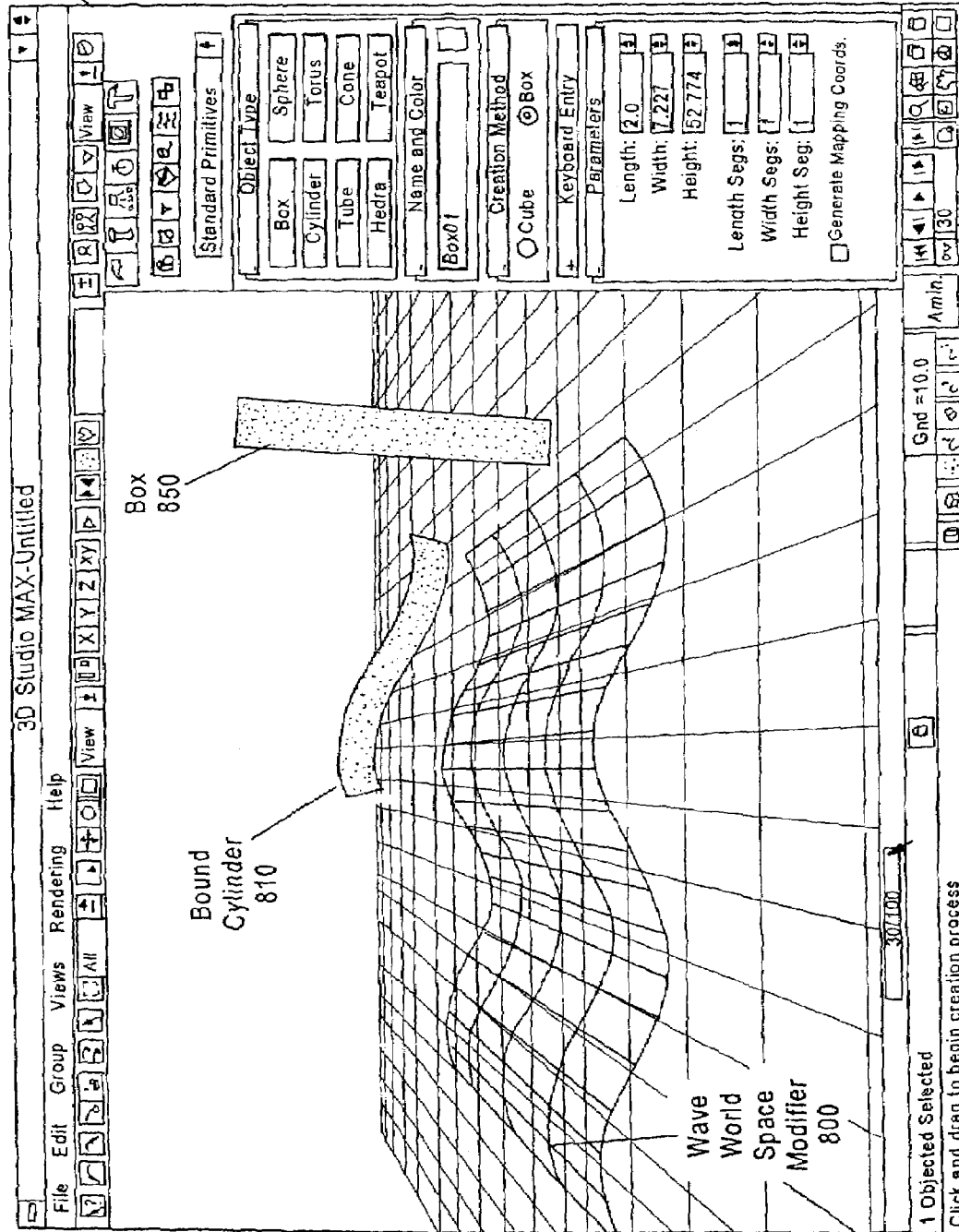


Figure 11

Frame
Indicator
840

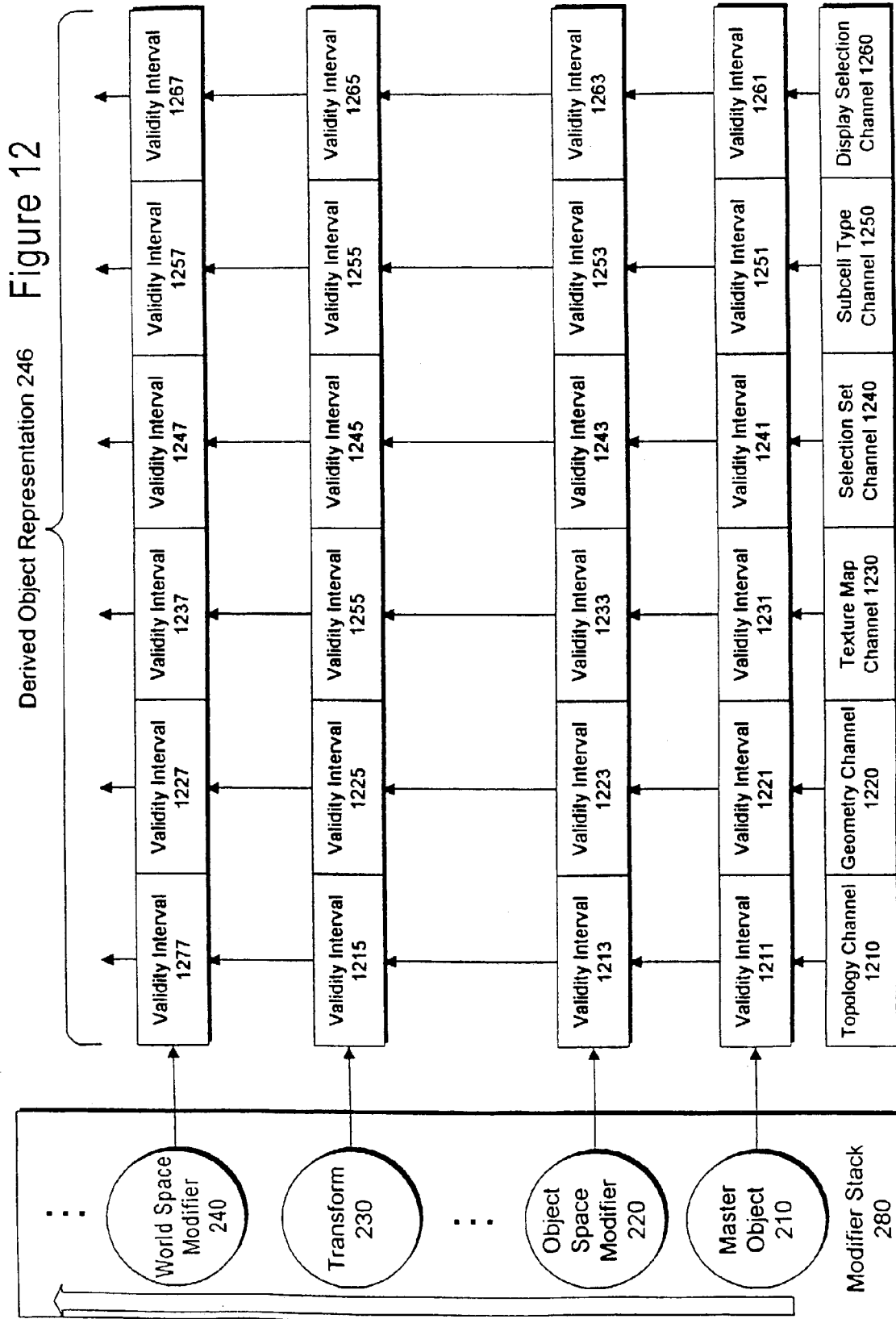
Box
850

Bound
Cylinder
810

Wave
World
Space
Modifier
800

1 Object Selected

Click and drag to begin creation process



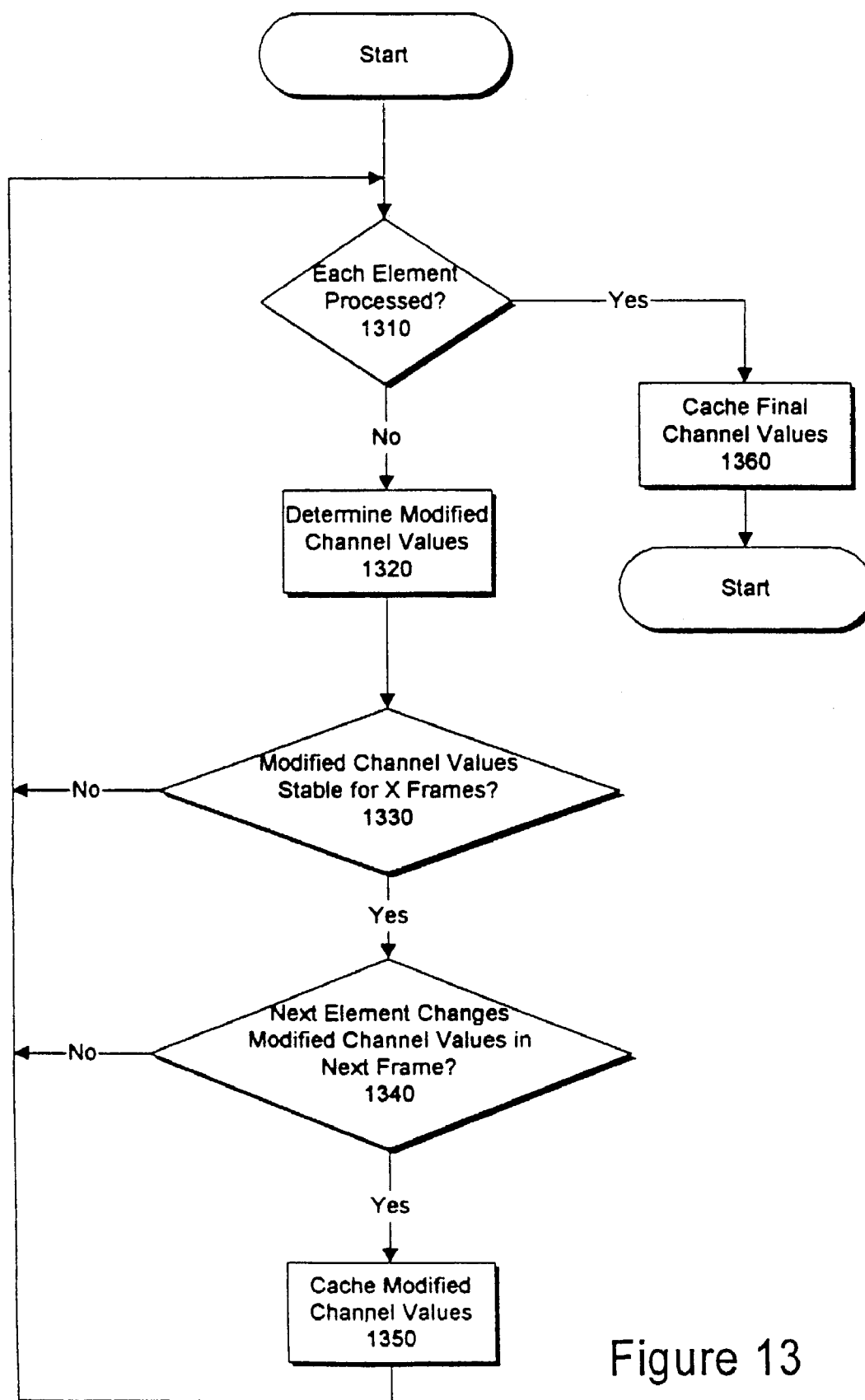
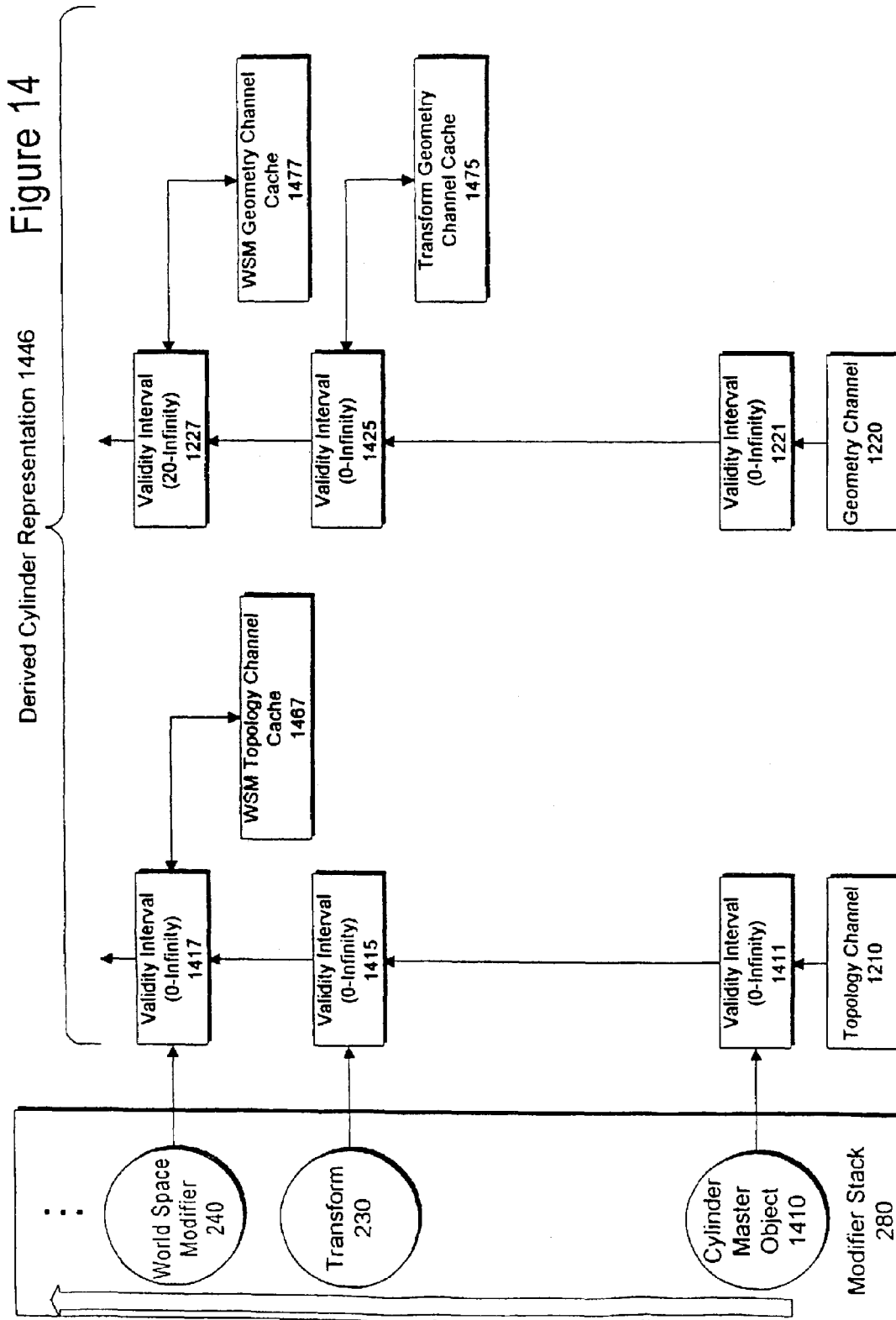


Figure 13



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THREE DIMENSIONAL MODELING AND ANIMATION SYSTEM USING MASTER OBJECTS AND MODIFIERS

RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 09/282,590, entitled "Three Dimensional Modeling and Animation System", filed Mar. 31, 1999, now U.S. Pat. No. 6,650,339 by inventors Daniel David Silva, Rolf Walter Berteig, Donald Lee Brittain, Thomas Dene Hudson, and Gary S. Yost, which is incorporated herein by reference and which claims the benefit of U.S. patent application Ser. No. 08/903,958, entitled "Applying Modifiers to Objects Based on the Types of the Objects", filed Jul. 31, 1997, now U.S. Pat. No. 6,061,067 by inventors Daniel David Silva, Rolf Walter Berteig, Donald Lee Brittain, Thomas Dene Hudson, and Gary S. Yost, which is incorporated herein by reference and which claims the benefit of U.S. provisional patent application No. 60/025,117, entitled, "Three Dimensional Modeling and Animation System," filed Aug. 2, 1996, by inventors Rolf W. Berteig, Daniel D. Silva, Donald L. Brittain, Thomas D. Hudson, and Gary S. Yost, which is incorporated herein by reference.

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BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates generally to field of three dimensional modeling and animation. In particular, the invention relates to an improved three dimensional modeling and animation system having an object oriented architecture.

2. Related Art

Three dimensional modeling systems allow users to generate models of three dimensional objects using computers. In previous systems, a user defines a simple three dimensional (3D) object and then applies various modifications (e.g., stretch, bend) to that object. The modifications change the way the object looks. To apply a modification, a user is prompted with a dialog box to fill in the values of the modification. The user then applies the modification to the object and views the results.

One problem with such a system is that the user does not have a good idea of how a specific modification will affect an object until after the modification is applied to the object. Additionally, it can be difficult to understand exactly how a specific modification affects an object from the look of the object after the modification is applied. This is because it can be difficult to understand the interactions between various modifications, already applied to the object, and the new modification.

Therefore, it is desirable to have a 3D modeling system that is simpler for the user to use by allowing the user to better understand how a particular modification to an object will affect the look of that object.

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SUMMARY OF THE INVENTION

One embodiment of the invention includes a method of generating a three dimensional (3D) representation of a modeled object on a display device of a computer system. The modeled object is represented by an initial definition of an object and a set of modifiers. Each modifier modifies some portion of the definition of an object that may result in a change in appearance of the object when rendered. The modifiers are ordered so that the first modifier modifies some portion of the initial definition of the object and produces a modified definition. The next modifier modifies the results of the previous modifier. The results of the last modifier are then used in rendering processes to generate the 3D representation.

In one embodiment, the modifiers are easily shared, the order of the modifiers is easily changed, and the values associated with the modifiers is also easily changed. These features provide the user with great flexibility in modeling and animation.

In one embodiment, the modifiers are associated with three dimensional visual representations that allow a user to better visualize and change the effect of a particular modifier.

In one embodiment, intermediate channel results created during the generation of a representation of an object are cached thereby increasing the speed of this embodiment. In particular, the representation of the object is generated in multiple channels, each channel representing some portion of that representation. Intermediate channel results are generated in each channel by elements in that object's list of modifiers. Depending on for how long these intermediate channel results are valid, the intermediate channel results may or may not be cached. In particular, in one embodiment, if it is determined that one set of intermediate channel results will be valid for a predetermined period of time, while the next intermediate channel results in that channel will not be valid for a predetermined period of time, then the intermediate channel results are cached.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other features and advantages of the invention will become more apparent to those skilled in the art from the following detailed description in conjunction with the appended drawings in which:

FIG. 1 illustrates a 3D modeling and animation system according to one embodiment of the invention.

FIG. 2 illustrates a how objects are rendered in the 3D modeling and animation system of FIG. 1.

FIG. 3 illustrates an object.

FIG. 4 illustrates an object having an object space modifier and corresponding gizmo.

FIG. 5 illustrates a second object space modifier applied to the object of FIG. 4.

FIG. 6 illustrates changes to the modifier stack of the object of FIG. 5.

FIG. 7 illustrates further changes to the modifier stack of the object of FIG. 5.

FIG. 8 illustrates a key frame and the start of an animation sequence.

FIG. 9 illustrates a "between frame" of the animation sequence.

FIG. 10 illustrates a second key frame of the animation sequence.

FIG. 11 illustrates a third key frame of the animation sequence.

FIG. 12 illustrates an example of the use of channels in generating a derived object's representation.

FIG. 13 illustrates one embodiment of a method of caching.

FIG. 14 illustrates an example of caching.

The figures illustrate the invention by way of example, and not limitation. In the figures, like references indicate similar elements.

DETAILED DESCRIPTION

1. Terminology

In this description, the term "instance" means an instance of class as in an object oriented programming language. In particular, "instance" does not mean an instance as defined in the 3D Studio Max™ User Guide, Volume 1 and 2, unless specifically noted. Also note that an "instance" in the object oriented sense can also be an "instance" in the 3D Studio Max™ application sense.

The term "reference" generally means a reference created through the use of the ReferenceTarget and ReferenceMaker classes, or the like, as described below.

2. System Overview

One embodiment of the invention includes an apparatus and method of generating a three dimensional (3D) representation of a modeled object on a display device of a computer system. The description of specific applications is provided only as examples. Various modifications to the preferred embodiments will be readily apparent, and the general principles defined herein may be applied to other embodiments and applications without departing from the spirit and scope of the invention. Thus, the invention is not intended to be limited to the embodiments shown, but is to be accorded the widest scope consistent with the principles and features disclosed herein.

3. Computer System

FIG. 1 illustrates a computer system 100 that can be used to implement the one embodiment of the invention. FIG. 1 also illustrates an example of a tube as modeled by one embodiment of the invention. The following describes the elements of FIG. 1 and then their operation.

The computer system 100 comprises a processor 110, a memory 140, an input device 120 and a display device 130. These components can communicate with each other via a bus 150. The memory 140 includes software such as the 3D modeling and animation application 145. The 3D modeling and animation application 145 includes, among other things, a scene 142. The scene 142 includes at least a first node 144, a corresponding derived tube 146 and a tube modifier stack 199. The tube modifier stack 199 includes a tube master 190, a bend modifier 192, and a twist modifier 194. The display device 130 displays the 3D modeling and animation interface 135 which shows a 3D representation of the derived tube 146 and the corresponding tube modifier stack 199.

The computer system 100 includes an IBM compatible personal computer, available from Hewlett-Packard, Inc. of Mountain View, Calif. In another embodiment, the computer system 100 includes one of a Macintosh™ computer, available from Apple Computer, Inc. of Cupertino, Calif., a SparcStation™ workstation, available from Sun Microsystems, Inc., of Mountain View, Calif., and a workstation from Silicon Graphics, Inc. of Mountain View, Calif. In one embodiment, the computer system 100 executes an operating system such as Windows 95™ or Windows NT™, available from Microsoft, Inc. of Redmond, Wash.

The computer system 100 need only have some type of processor 110 for executing instructions and manipulating data. In one embodiment, the processor 110 includes a distributed processing system such that processing is done by a number of networked microprocessors.

The memory 140 stores data and instructions. The memory 140 includes one or more of: a random access memory, a read only memory and a hard disk memory.

The input device 120 allows the user to interact with the 3D modeling and animation application 145. The input device 120 includes one or more of: a keyboard, a mouse, and a trackball. Importantly, the input device 120 includes some device allowing the user to interact with the 3D modeling and animation application 145.

The display device 130 displays the 3D modeling and animation interface 135. The display device 130 includes a cathode ray tube (CRT) display, flat panel display, or some other display device. In the example of FIG. 1, the 3D representation of the scene 142 is shown in a perspective view 132.

The 3D modeling and animation application 145 includes data and instructions for creating 3D models, photo-realistic still images, and film quality animation. The 3D modeling and animation application 145 uses a process called "rendering" to determine the correct display device 130 representation of the scene 142. One embodiment of the invention includes the application 3D Studio Max™, available from Autodesk, Inc. of San Rafael, Calif.

The scene 142 includes all the objects to be displayed in the 3D modeling and animation interface 135. An object is thus something in a scene 142. Further, an object is a model of a physical object, such as a cylinder, tube, box and teapot, or an object is a non-physical object used in modeling other objects, such as a wave, a bomb, or a deflector. Each object corresponds to a graphical representation in the 3D modeling and animation interface 135. Of course, some objects may not be displayed because, for example, the display option is in the 3D modeling and animation interface 135 do not allow that particular object to be displayed, because one object is blocking another object, or because the user has requested that the object not be displayed. Objects are described in greater detail below.

The scene 142 is made up of a number of nodes, such as node 144. Each node is associated with some object. In the example of FIG. 1, the node 144 is associated with a derived tube 146 object. The derived tube 146 is a model of a physical object; in this case, a tube that has been bent and twisted. The bent and twisted tube is shown as the derived tube's graphical representation 134. Note the invention allows for much more visually complex objects to be rendered, but for FIG. 1, an example of a relatively simple object is described.

The derived tube 146 has a modifier stack, labeled as tube modifier stack 199. The tube modifier stack 199 is a simplified example of a modifier stack. The modifier stack is described in greater detail below. The tube modifier stack 199 includes the tube master 190 (a parametric object), the bend modifier 192 and the twist modifier 194. The tube master 190 includes a parametric definition of a tube, e.g. a tube has an inner radius, an outer radius and a height. The bend modifier 192 modifies the definition of the tube so that the tube will appear bent. The twist modifier 194 modifies the definition of the bent tube to that the bent tube is also twisted. How the modifiers work in connection with the master objects is described in greater detail below. However, importantly, the use of modifier stacks, in one embodiment

of the invention, provides the user with previously unequaled ease of use and flexibility in 3D modeling and animation.

The following describes the general operations in the computer system **100** used in the rendering process. The computer system **100**, using the processor **110** and the memory **140**, executes the 3D modeling and animation application **145** which renders a three-dimensional (3D) representation of the scene **142** on the display device **130**. As part of the rendering process, the derived tube **146** provides a parametric definition of a bent and twisted tube for use by the 3D modeling and animation application **145**. In this step, the derived tube **146** accesses the tube modifier stack **199** to generate the parametric definition of the bent and twisted tube. The 3D modeling and animation application **145** uses the parametric definition and various rendering techniques to generate the derived tube's graphical representation **134**. The 3D modeling and animation application **145** then causes the display device to display the perspective view **132**, including the derived tube's graphical representation **134**. Thus, given a scene with a derived object, the computer system **100** can render a representation of that object.

The above has described an overview of a computer system that supports 3D modeling and animation using modifier stacks. The next section describes the class hierarchy used in the 3D modeling and animation application **145** that enable the use of modifier stacks. Following the next section is a description of the how these classes are used together in the application.

4. Objects and Their Relation to Scenes

In one embodiment of the invention, the 3D modeling and animation application **145** has an object oriented design. Thus, the application has a class hierarchy that supports inheritance. This section describes the class hierarchy used to create modifier stacks. Table 1 illustrates the class hierarchy in one embodiment of the 3D modeling and animation application **145**. Each of the classes is described below.

TABLE 1

Animatable
ReferenceMaker
ReferenceTarget
BaseObject
Modifier
Object
GeometricObject
TriObject
SimpleObject
PatchObject
ParticleObject
SimpleParticle
ShapeObject
SplineShape
SimpleSpline
LinearShape
SimpleShape
WorldSpaceModifierObject
SimpleWorldSpaceModifierObject

i. Animatable Class

The Animatable class is the superclass of all the animatable classes. Although no instances of Animatable are used, instances of the Animatable's subclasses include methods that support the animation of an instance of that particular subclass. Also, the Animatable class includes a class identifier and associated properties.

ii. ReferenceMaker & ReferenceTarget

The ReferenceMaker class and the ReferenceTarget classes work together to support references between objects

in a scene. A reference within a scene occurs when one object depends upon another object for rendering. For example, one embodiment of the invention allows different objects (e.g. two derived tubes) to share the same master object. In this example, the master object becomes the target of references from the objects. The reference allows a scene to be rendered and allows for the use of modifiers by multiple objects. As is described below, this use feature provides a user with significant benefits over previous systems. The reference also allows changes in the master object to be broadcast to any objects that are referring to that master object. The ReferenceMaker class includes the methods for indicating that a particular instance depends on another instance. The ReferenceMaker class also includes methods for receiving messages from reference target objects when changes are made to that reference target object. The ReferenceTarget class includes the methods for indicating that a particular instance is target of a reference. The ReferenceTarget class supports the broadcast of messages to all referring reference maker objects about changes to that reference target object. As with the Animatable class, no instances of ReferenceMaker or ReferenceTarget are used in the application, instances of these classes' subclasses are used instead.

In one embodiment of the invention, references support a technique called lazy evaluation. Lazy evaluation increases the performance the 3D modeling and animation application **145**. The purpose of lazy evaluation is to reduce the number of unnecessary calculations by not performing any evaluations until specifically requested.

The following describes an example of lazy evaluation. Assume that to properly render a first object, that first object must receive data from a second object (e.g., the first object includes an instance of a LinkedXForm which uses the local coordinate space of the second object to scale the first object. LinkedXForms are described below). This relationship is established via a reference from the first object to the second object. If the data in the second object is changed, then the second object will broadcast the change to the first object. In lazy evaluation, the first object does not recalculate any changed values (e.g., its geometry parameters) until the first object is specifically requested (e.g., a request to provide a derived object representation, described below). In lazy evaluation, the first object merely marks its dependent values as no longer valid. Thus, the first object does not precompute the new values until it needs to provide these values.

iii. BaseObject

The BaseObject class includes the methods for providing a three dimensional graphical representation of an object on the display device **130**. The BaseObject class includes methods for providing different display methods (e.g., bounding box, wireframe) for each of its subclasses. In one embodiment, these display methods are overridden by equivalently named methods in the BaseObject's subclasses.

iv. Modifier

The Modifier class includes the methods for modifying objects during the rendering process. Instances of the Modifier's subclasses provide a set of very powerful and flexible features that greatly enhance the usability of the 3D modeling and animation application **145**. Each instance of a Modifier subclass has methods for causing a particular modification of an object, such as a bend or a twist. Modifiers change the look of an object by, for example, changing the object's vertices or the object's topology. Modifiers can be stacked together so that the output of one modifier is fed into the input of another modifier. This

provides a user with a virtually endless number of combinations. Modifiers can also be shared through references.

In one embodiment, each Modifier subclass modifies only specific types of objects. For example, in this embodiment, instances of the Bend class can modify geometric objects and shape objects while instances of the EditSpline class can only modify shape objects.

There are two main subclasses of Modifier: ObjectSpaceModifier and WorldSpaceModifier. These classes are described next.

v. ObjectSpaceModifier

The ObjectSpaceModifier class is a subclass of the Modifier class. The ObjectSpaceModifier class is the superclass of the object space modifier classes. Before further describing the class, the various coordinate spaces relevant to one embodiment of the invention are described.

Different spaces are used in one embodiment of the invention to differentiate different sets of spatial coordinate systems. In one embodiment of the invention there are two relevant spatial coordinate systems, object space and world space.

Object space is the coordinate system unique to each object in the scene 142. In one embodiment, every object has a local center and coordinate system defined by the location and orientation of the object's pivot point. The local center and coordinate system of an object combine to define that object's object space.

World space is the universal coordinate system used to track objects in a scene 142. World space relates the coordinates defining an object to the other objects in the scene 142. An object in a scene is located in world space by that object's position, rotation and scale (its transforms).

Returning to the description of the ObjectSpaceModifier class, instances of the subclasses of ObjectSpaceModifier modify an object in object space. For example, a bend is an object space modifier that causes an object's definition to change so that some portion of the object is bent relative to some other portion of that object.

The following describes the types of object space modifiers available in one embodiment of the invention. Object space modifiers can be divided into general, specialized and edit shape modifiers. The general object space modifiers have real-world equivalents and are relatively simple to understand. In one embodiment, the general object space modifiers include: bends, ripples, skews, tapers, twists, and waves. In this embodiment, the special modifiers include: displace, noise, and optimize. Also in this embodiment, the edit shape modifiers include edit splines, extrudes and lathes. In one embodiment, Bend, Ripple, Skew, Taper, Twist, Wave, Displace, Noise, Optimize, XForm, LinkedXForm, VolumeSelection, EditSpline, Extrude and Lathe are all subclasses of the superclass ObjectSpaceModifier.

Bend—produces a uniform bend in an object's geometry. The angle and direction of the bend is set as well as the bend axis. The bend modifier has a limit value that limits the bend to a particular section of an object's geometry.

Ripple—produces a concentric rippling effect in an object's geometry. The size of the waves of the ripple are set. Ripple has a corresponding modifier in the world space.

Wave—produces a wave effect in an object's geometry. The size and phase of the wave is set. One embodiment of the invention supports a decay value that decreases or increases the size of the wave. Wave also has a corresponding world space modifier.

Skew—produces a uniform offset in an object's geometry. The amount and direction are set for each instance of skew. A skew's effect can also be limited so that only a portion of an object is skewed.

5 Taper—produces a tapered contour by scaling one end of an object's geometry. Each taper instance has values for the amount of taper and curve of the taper on two sets of axes. The taper's effect can also be limited to a section of the object's geometry.

10 Twist—produces a twist like a screw's thread in an object's geometry. Each instance of Twist has values for the angle of the twist on any of three axes, and a bias that compresses the threads relative to the pivot point of the object. The twist's effect can also be limited to a section of the object's geometry.

15 Displace—reshapes the geometry with a variable force. One embodiment of the invention has a corresponding Displace class that is a subclass of WorldSpaceModifier.

Noise—simulates random motion in an animated object. 20 Noise also produces fractal effects that are useful in creating terrain features, for example.

Optimize—reduces the number of faces and vertices in an object. The purpose of Optimize is to simplify the geometry and increase the speed of rendering while maintaining an acceptable image.

25 XForm—acts as a transform for all or a portion of an object but is evaluated as a modifier. The importance of the order of execution of modifiers and transforms is described in greater detail below.

30 LinkedXForm—works in the same way as XForm except that the LinkedXForm uses the coordinate system of another object.

EditSpline—changes the splines, segments and vertices of a shape object. Shape objects are described below in conjunction with the description of the Object class.

35 Extrude—creates a 3D object by sweeping a shape along a straight line.

Lathe—creates a 3D object by revolving a shape along an axis.

(1) Manipulating Object Space Modifiers

Before describing world space modifiers, a description of a method of interacting with object space modifiers is described. One embodiment of the invention not only allows a user to change the parameters of an object space modifier by directly entering the values of the parameters, but also allows the user to manipulate a 3D representation of the modifier.

50 In one embodiment, the 3D representation of the modifier is called a gizmo. The gizmo is a wireframe representation of that gizmo's modifier. A gizmo acts like a mechanical apparatus that transfers the modification to the object that gizmo is attached to. That is, by changing the gizmo, the user is changing the values of the parameters of the modifier. A user can move, scale and rotate a gizmo as is done with any other object.

In one embodiment, the gizmo represents parameters of a modifier that are not otherwise easily definable and/or accessible by a user. For example, a modifier may have a center, defined by an {x, y, z} coordinate, a scale along each axis, and a rotation along each axis. This is a great deal of information. However, by providing the user with a three dimensional representation of this modifier information, the user can quickly visualize this information and change it, thereby changing these values and in turn changing the effect of the modifier on the object.

In one embodiment, world space modifiers also have gizmos. In another embodiment, an instance of a world space modifier uses a world space modifier object to change the parameters of the world space modifier.

vi. World Space Modifier

Like instances of the `ObjectSpaceModifier` class, instances of the `WorldSpaceModifier` class affect the appearance of other objects. The difference being that world space modifiers affect objects in world space coordinates. Also like the `ObjectSpaceModifier` class, `WorldSpaceModifier` has a number of subclasses that can be instantiated to modify objects in different ways.

One or more objects are modified by a world space modifier by binding those objects to the world space modifier. In one embodiment, the binding process is performed by creating a reference between the world space modifier and each object that is bound to that world space modifier. A world space modifier has no effect on an object in a scene **142** that is not bound to the world space modifier. Importantly, when multiple objects are bound to the same world space modifier, the world space modifier's parameters affects all the objects equally. However, each object's distance from, and spatial orientation to, the world space modifier can change the world space modifier's effect. Because of this spatial effect, simply moving an object through the world space can change the warp's effect. This last feature provides a user with a powerful tool in animations. For example, to show a dolphin swimming, a user need only model the dolphin and then bind the dolphin to an instance of a `Wave` world space modifier. As the dolphin object translates through the world space, the dolphin will be modified by the wave to appear to be swimming. Additionally, an object can be bound to multiple world space modifiers.

In one embodiment, each world space modifier includes a graphical representation of itself. As noted above, this graphical representation is a gizmo in one embodiment, and in another embodiment, this graphical representation is an instance of a subclass of the `Object` class.

The following is a list of subclasses of `WorldSpaceModifier`, in one embodiment:

Bomb—explodes a geometric object into individual faces that over time become disjoint in space. Thus, the **Bomb** subclass is particularly useful in animations.

Deflector—acts as a shield to repel the particles generated by a particle system object. A deflector can be used to simulate pavement being struck by rain, or a rock in the middle of a waterfall.

Displace—acts much like the `ObjectSpaceModifier Displace` class except the effect is in world space.

Gravity—simulates the effects of gravity on particles generated by a particle system object. Gravity instances are directional. To create a waterfall with a rock in the middle, instances of **Gravity** and **Deflector** classes can be combined.

Ripple—acts much like the `ObjectSpaceModifier Ripple` class except the effect is in ace.

Wave—acts much like the `ObjectSpaceModifier Wave` class except the effect is in ace.

Wind—simulates the effect of wind blowing particles generated by a particle system

As noted above, each `Modifier` subclass knows which objects it can modify. In the above embodiment, the **Bomb**, **Display**, **Gravity**, **Ripple** and **Wave** classes modify geometric objects. The **Deflector**, **Displace**, **Gravity** and **Wind** modifiers modify particle system objects.

One embodiment of the invention includes a plug-in architecture that allows additional object space and world space modifiers to be added to the 3D modeling and animation application **145**.

vii. Object

As noted above, the term object refers to something in the scene **142**. In one embodiment, all objects are defined by three general properties: a collection of creation parameters, a pivot point, and a bounding box. The properties describe the form, local origin, initial orientation, and the extent of an object.

The `Object` class is the superclass of all the different types of objects in a scene. In one embodiment, the `Object` class has the following subclasses: `GeomObject` (geometry object), `Shape Object`, `WorldSpaceModifierObject`, and `DerivedObject`.

The `GeomObject` class is the superclass of basic renderable objects, such as tubes, cylinders, boxes, polyhedra, spheres, torus, and cones. One embodiment of the invention includes the following geometric object categories.

Standard Primitives—3D geometric objects such as **Box**, **Sphere**, and **Cylinder**.

Patch Grids—are 2D surfaces.

Particle Systems—are animated objects that simulate rain, snow, dust and similar collections of small objects.

Shapes—include 2D objects line lines and donuts and 3D spline-based shapes like a helix. Shape objects are not directly renderable in one embodiment. The shape objects need to first be modified before they are renderable.

World Space Modifier Object—is not a renderable object, but is still visible to the user. A world space modifier object is like a gizmo for an object space modifier. The world space modifier object provides a visual representation of a world space modifier that allows the user to bind an object to the corresponding world space modifier.

Derived Object—includes a list of modifier objects and a pointer to the master object. In rendering a scene, a user always sees a derived object, even if no modifiers are applied to an object. The reason for this is that the derived object not only ensures that a particular object is correctly rendered, but also that an appropriate cache is maintained for that particular object. The caching abilities of the derived objects is an important performance enhancing feature of one embodiment of the invention and is described in greater detail below.

The above class hierarchy illustrates only one class hierarchy. Other embodiments include other class hierarchies. For example, in one embodiment, the classes under the `ShapeObject` are moved under the `GeometricObject` class. In another embodiment, the methods in the `Animatable`, `ReferenceMaker` and `ReferenceTarget` classes are combined into the `BaseObject` class. In another embodiment, the `ReferenceTarget` is a superclass of the `ReferenceMaker`. In another embodiment written in a language that supports multiple inheritance, `ReferenceMaker` does not inherit from `Animatable`, nor does `BaseObject` inherit directly from `ReferenceTarget`, however the `Modifier` class and the `Object` class multiply inherit from the `Animatable`, `ReferenceTarget` and `BaseObject`.

5. Pipeline for Rendering

FIG. 2 and the following describe how objects in a scene **142** are rendered in one embodiment of the 3D modeling and animation application **145**. So as not to obscure this embodiment of the invention, **FIG. 2** has been simplified. The following first describes the elements of **FIG. 2** and then the operation of those elements.

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FIG. 2 includes an application control module 200, a derived object 270, a modifier stack 280, a master object 210, an object space modifier 220, a transform 230, a world space modifier 240, a rendering pipeline 250 and a display buffer 260. These elements work together to render a graphical representation of the derived object onto the display device 130.

The application control 200 controls the operation and interaction between the elements of FIG. 2. In one embodiment, the application control 200 includes the 3D Studio Max core software architecture. However, what is important is that there is some method of controlling the various elements in FIG. 2.

The derived object 270 is part of a scene 142 (not shown) and is responsible for ensuring that a modified object is properly rendered. The derived object is an instance of the DerivedObject class. The derived object instance is created when a user creates an object in a scene.

In one embodiment, each derived object 270 maintains a modifier stack 280. In one embodiment, the modifier stack 280 includes a list of modifiers (e.g. object space modifier 220 and world space modifier 240), a transform, and a pointer to a master object 210. In another embodiment, the derived object 270 maintains a reference to the master object 210, a reference to the transform 230, and a list of modifiers. However, what is important is that the derived object 270 maintains the information necessary to generate a description of a modified object (labeled as the derived object representation 246).

A more detailed description of the elements in the modifier stack 280 is now provided. The master object 210 includes a parametric definition of an instance of a subclass of Object (e.g. the topology (e.g., mesh, direction of faces) and geometry (e.g., vertices and edges)). Importantly, the user does not see the master object 210 but sees the rendered result of the modifiers and transform identified by the derived object 270. The object space modifier 220 is an instance of a subclass of the class ObjectSpaceModifier. The transform 230 is responsible for transforming points in the object space coordinate system to corresponding points in the world space coordinate system. Unlike modifiers, the transform 230 are independent of an object's internal structure. The transform 230 acts directly on the object's local coordinate system. The local coordinate system for an object can be expressed as a matrix of values that specify the following information in world space: position of the object's center, rotation of the object in world space, and the scale of the object along its local axes. The world space modifier 240 is an instance of a subclass of the class WorldSpaceModifier. The modifier stack 280 includes zero or more object space modifiers and world space modifiers.

In response to a request for a representation of itself, the derived object 270 provides the application control 200 with a derived object representation 246. Depending on the type of rendering being done and the type of master object 210, the derived object 270 will provide a bounding box, topology, geometry and/or texture map description of the modified and transformed master object 210. How the derived object 270 creates the derived object representation 246 is described below.

The derived object representation 246 is then used by the rendering pipeline 250 to create a bit pixel data 256 representation of the modified and transformed object. The rendering pipeline 250 includes processes for converting the parameter information in the derived object representation 246 into pixel data. In one embodiment, the rendering pipeline includes rendering processes such as smoothing,

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highlighting, facets, lit wireframe, wireframe and bound box. In one embodiment, known rendering techniques are used in the rendering pipeline 250. The pixel data 256 includes the pixel information for display on display device 130. The display buffer 260 holds the pixel data for display by the display device 130.

How the derived object 270 creates the derived object representation 246 is now described. When a derived object 270 is asked by the application control 200 to provide a renderable description of itself, the derived object 270 evaluates the master object 210, then any object space modifiers, the transform, and then any world space modifiers, to generate the derived object representation 246. That is the master object 210 provides the basic description of the object. This basic description is then provided to the first object space modifier in the modifier stack 280. The object space modifier modifies this basic description to generate a modified description. The next object space modifier is then evaluated to modify the previous modified description. This process continues until each object space modifier has been evaluated. Importantly, the object space modifiers are evaluated in the order they appear in the object modifier stack 280. Next the transform 230 is evaluated. Each derived object 270 has only a single transform 230 and that transform is always evaluated after the object space modifiers 220. If a user wishes to apply a transform before one or more object space modifiers, the user can use an instance of the XForm object space modifier class. After the transform 230, the world space modifiers 240 are evaluated. The world space modifiers are evaluated in a manner similar to the object space modifiers. In particular, the world space modifiers 240 are evaluated in the order that they are added to the modifier stack 280.

As noted above, the modifier stack 280 makes modeling and animation significantly easier for the user. Some advantages of having the modifier stack 280 are described below.

6. Using the Modifier Stack

This section describes how to use the modifier stack 280 and provides examples of using the modifier stack for modeling and animation. FIG. 3 through FIG. 7 illustrate an example of creating and modifying a tube using a modifier stack 280. FIG. 8 through FIG. 11 illustrate an example of animating a cylinder using a modifier stack 280.

i. Modeling and the Modifier Stack

Each time a new object is instantiated by a user, a derived object 270 is created. In the example of FIG. 3, a tube 300 is created and rendered to the 3D modeling and animation interface 135. To the right of the interface, the parameters defining the tube are shown in the tube definition 310. At this point, the modifier stack 280 only includes the reference to the tube master object 210 and the transform 230 for the tube.

FIG. 4 illustrates a bend modifier as it is applied to the tube 300. When the tube 300 is selected, the 3D modeling and animation interface displays the modifier stack interface 420 for the tube 300. The modifier stack interface 420 shows that the bend modifier has been selected for display. Because the bend is selected, the bend definition 410 appears. The bend definition 410 shows the parameters for the bend. In this case, the angle of the bend is ninety degrees and the direction is ninety degrees, both along the Z axis.

Also shown in FIG. 4 is an example of a gizmo, the bend gizmo 430. The bend gizmo allows the user to change the values of the bend modifier without having to enter the values directly into the bend definition 410 interface.

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FIG. 5 illustrates an additional twist modifier as it is applied to the bent tube 300. The modifier stack edit window 520 is also displayed. The modifier stack edit window 520 shows that the tube 300 has a bend applied first and then a twist. Importantly, the modifier stack 280 allows a user to easily add modifiers to an object and view not only the results of the new modifiers but also view a list of all the modifiers that apply to an object.

The modifier stack 280 also allows a user to edit modifiers that are anywhere in the modifier stack 280. For example, the user can change the values of the bend modifier without having to “undo” the twist modifier first.

In one embodiment, the user can change the order of the modifiers. As noted above the order of evaluation of the modifiers is important for some modifiers. For example, applying a bend before a twist can have a significantly different look than applying a twist before the bend.

Additionally, the user can disable a particular modifier, but keep the modifier in the modifier stack 280. FIG. 6 illustrates an example of this feature. The tube with the bend and twist 600 is the same tube as is illustrated in FIG. 5. The tube with the bend disabled 610 shows the same modified object except that the bend modifier has been disabled in this tube’s modifier stack. The bend disabled indicator 630 indicates that the bend modifier for the tube 610 has been disabled. In one embodiment, to enable the bend, the user need only select the bend disabled indicator 630.

FIG. 7 illustrates the tube with a bend and twist 600 as well as a tube with a bend disabled and a transform modifier 710. The modifier stack of the tube with the bend disabled and the transform modifier 730 is also shown. Importantly, the user was able to easily change the order of the twist and bend, keep the bend disabled, and insert an XForm instance between the two modifiers.

ii. Animation and the Modifier Stack

As noted above, in addition to helping in modeling, the modifier stack 280 is helpful in animating a model. Before describing the examples of FIG. 8 through FIG. 11, it is helpful to describe the animation process first.

The user creates key frames that record values of various parameters at the beginning and end of each animated sequence. The values at the keyframes are called keys. The 3D modeling and animation application 145 determines the interpolated values between each key to produce “between frames” that complete the animation. The 3D modeling and animation application 145 can animate many parameters in a scene 142. For example, modifier parameters can be animated such as a bend angle, and a taper amount.

Note that other embodiments of the invention allow the user to create an animation by not using key frames but by using controllers which are not key based, e.g., noise.

FIG. 8 illustrates the beginning of a thirty frame animation sequence (frame zero is shown in the frame indicator 840). FIG. 9 illustrates results of the animation at frame fifteen. FIG. 10 illustrates the results of the animation at frame twenty. FIG. 11 illustrates the end of the animation sequence at frame thirty.

The elements in FIG. 8 through FIG. 11 are: the bound cylinder 810, the wave world space modifier 800 and the box 850. The bound cylinder 810 is bound to the wave world space modifier 800.

FIG. 8 shows the bound cylinder 810 rendered to the left side of the perspective view. The box 850 is relatively short. FIG. 8 is a key frame that defines the position, size, rotation, and the effects of any modifiers on the bound cylinder 810 and the box 850 at frame zero of the animation.

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FIG. 9 shows the bound cylinder 810 partly translated to the right. FIG. 9 is not a key frame, but an interpolated frame from the values defined in the frame zero key frame and the key frame at frame twenty. Note that the wave world space modifier 800 has modified the look of the bound cylinder 810. Also shown in FIG. 9 is that the box is now taller than in FIG. 8.

FIG. 10 shows the key frame where the bound cylinder 810 has completed its translation across the screen. To create this key frame, the user accessed the modifier stack 280 of the bound cylinder at frame twenty and changed the position of the bound cylinder 810 by modifying the values of the transform 230 for the bound cylinder 810. The 3D modeling and animation application 145 interpolated the values of the transform at the key frame zero and the key frame twenty to create the between frames including the between frame shown in FIG. 9.

FIG. 11 shows the last key frame in the sequence, frame thirty. In this frame, the bound cylinder 810 has not changed location because after frame twenty, there were no more key frames that affected the bound cylinder 810. However, frame thirty has a key value for the box 850. Thus, the box 850 has continued to grow in size from frame twenty. Again to enable the box to grow until frame thirty, the user had previously changed the value of the transform in the modifier stack 280 of the box 850 at frame thirty.

Importantly, the user can animate many of the parameters in the modifier stacks 280 of the objects in a scene. Thus, the animation of objects is much easier than in previous systems.

7. Caching

As noted above, one embodiment of the invention provides a significant speed increase over prior systems. This embodiment of the invention achieves the speed increase by caching portions of the derived object representation 246 within each derived object 270. The following describes how the values of the derived object representation 246 are determined and then how these values are cached.

i. Channels

In one embodiment of the invention, each derived object 270 provides the derived object representation 246 in response to a request to provide that information. However, the contents of that information may vary depending on the type of request. For example, a bounding box representation need not have the same detailed information as a smoothed representation. Additionally, during an animation, for example, only part of a derived object representation 246 may change. For example, as shown in the FIG. 8 through FIG. 11, during the animation, the topology of the bound cylinder does not change, but the geometry does change. Therefore, even though the same request may be made of the derived cylinder (e.g., wireframe representation request, only the geometry values are changing in each frame of the animation. Given that different types of data may need to be generated because of the different types of messages, and that even for the same request only some of the data may change in the next frame, one embodiment of the invention divides the derived object representation 246 creation into value generating channels.

A channel corresponds to a different portion of a derived object representation 246. Each channel is responsible for generating its own portion of the derived object representation 246. Each element in the modifier stack 280 affects values in one or more of the channels. The results of an evaluation of a modifier in a channel is called an channel intermediate result. In one embodiment, providing a derived

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object representation **246** includes determining which channels need to be accessed. Next, evaluating the elements in the modifier stack **280** that affect the values in those channels. Evaluating the elements affecting that channel involves generating a series of channel intermediate results until the last element is evaluated. The results of evaluating the last element in the modifier stack is that channel's portion of the derived object representation **246**.

For example, the transform **230** affects values in at least the geometry channel in the derived object representation **246**. Therefore, an evaluation of the transform **230** in the geometry channel generates a set of geometry channel intermediate results. These intermediate results can then be passed onto the next element in the modifier stack **280** that effects the geometry channel. When the last element is evaluated, the geometry values are included in the derived object representation **246**.

As shown in FIG. **12**, one embodiment supports a topology channel **1210**, a geometry channel **1220**, a texture map channel **1230**, a selection set channel **1240**, a subcell type channel **1250** and a display selection channel **1260**. The topology channel **1210** determines the topology (e.g., the normal direction of the faces an object) of the derived object **270**. The geometry channel **1220** determines the geometry (e.g., vertices) of the derived object **270**. Most modifiers modify the geometry of the derived object **270**. The texture map channel **1230** determines the texture mapping coordinates of any texture mapped to the derived object **270**. The selection set channel **1240** determines an array of bits indicating which vertices are selected by a selection modifier. The subcell type channel **1250** determines the type of selection (e.g., for a mesh object, the selection type can be an edge or a vertex). The display selection channel **1260** determines how parts of the derived object are to be displayed (e.g., are vertices ticks to be displayed for the derived object **270**). Not every derived object **270** needs all of these channels. For example, if no texture map is mapped onto an object, the texture map channel **1240** is not needed by the derived object **270**.

ii. Caching in Channels

One embodiment of the invention includes the caching of the intermediate channel results. This embodiment of the invention not only includes determining the intermediate channel results, but also determining a time period for which those results are valid. This time period is called the validity interval. An example of a validity interval is where, for frame nineteen of the animation in FIG. **8** through FIG. **11**, the bound cylinder **810** has a geometry channel **1220** validity interval, for the wave world space modifier **800**, of frame twenty to frame infinity. Because the length of time an intermediate result of the derived object **270** is known to be valid, the validity interval helps optimize the caching of the intermediate channel results.

As shown in FIG. **12**, each element in the modifier stack **280** has an associated validity interval in each topology channel. For example, the object space modifier **220** has a validity interval **1213** for the topology channel **1210**, a validity interval **1223** for the geometry channel **1220**, a validity interval **1233** for the texture map channel **1230**, a validity interval **1243** for the selection set channel **1240**, a validity interval **1253** for the subcell type channel **1250** and a validity interval **1263** for the display selection channel **1260**.

In conjunction with FIG. **13**, the follow describes how the validity interval is used in the caching process. FIG. **13** illustrates the process of determining what to cache during the evaluation of elements for a specific channel of a derived object **270**.

Prior to the first step in FIG. **13**, the derived object **270** has received a request to provide a corresponding derived object

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representation **246**. The derived object **270** then determines which channels need to be evaluated. The derived object **270** also is aware of the time (e.g., which frame) the request is being made for.

At step **1310**, a test is made to determine whether each element in the modifier stack **280** has been processed. If all the elements have been processed, then step **1360** is performed. Otherwise, step **1320** is performed. In one embodiment, this includes testing whether the "present element" is the last element in the modifier stack **1280**.

At step **1320**, the next element in the modifier stack **1280**, now identified as the "present element", generates a corresponding set of intermediate channel results for that particular element and channel.

At step **1330**, the validity interval is determined, if not already determined from the last execution of these steps, for the present element. The present element's validity interval is tested to determine whether the present element is valid for the next N frames. (In another embodiment, the validity interval is tested to determine whether the present element's intermediate results are valid for a predetermined time period, a number of frames being only one example of the time period.) In one embodiment, N is ten. If the present element's validity interval is valid for the next N frames, then step **1340** is executed. Otherwise, step **1310** is executed.

At step **1340**, the validity interval for the next element after the present element in the modifier stack **280** is generated. This validity interval is tested to determine whether the intermediate results generated by the next element are valid for a predetermined period of time (e.g., the next frame, or the next five frames). If the next element is the top of the modifier stack, then this test returns false. The next elements validity interval is stored in one embodiment for use in step **1330** during the next iteration of these steps. If the next element's validity interval is not valid for the predetermined period of time, then the step **1350** is executed. Otherwise, step **1310** is executed.

At step **1350**, the intermediate channel results generated in step **1310** are stored in a cache for this derived object. Because of the tests performed in step **1330** and step **1340**, the system knows that the data in the cache is valid for at least the next N frames. Therefore, the next time this channel is evaluated (e.g., the next frame), rather than evaluating all of the elements in the modifier stack **280** below the present element, the derived object need only begin the evaluation at the next element in the modifier stack **280** for this channel.

At step **1360**, the results of evaluating the last element in the modifier stack **280** are cached. The results of the last element in the modifier stack **280** represent that channel's portion of the derived object **270**. Therefore, in one embodiment, if an derived object **270** is requested to provide its derived object representation **246**, with nothing changed in the derived object **270**, that derived object **270** need only provide the cached value. This greatly reduces the number of evaluations performed in the system.

FIG. **14** illustrates one example of the caching performed for the bound cylinder **810**. In the example of FIG. **14**, the cache is shown for frame nineteen of the animation. Also, in this example, only the topology channel **1210** and the geometry channel **1220** are shown. The following describes how the steps of FIG. **13** are used to cache intermediate results in the topology channel **1210** and the geometry channel for the bound cylinder **810**. The value for "X" in step **1330** is ten in this example.

For the topology channel **1210**, first step **1310** is executed which leads to step **1320**. At step **1320**, the cylinder master object is accessed (the present element of the bound cylinder's modifier stack) and the intermediate topology channel results are generated. In this case, the intermediate topology

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channel results are the GeometricObject instance topology definition with no modifications. At step 1330, the topology channel validity interval 1411 for the cylinder master object is determined to be zero to infinity. Also at step 1330, the validity interval 1411 is determined to be greater than ten frames; therefore, step 1340 is executed. At step 1340, the validity interval 1415 for the transform 230 is determined to also be zero to infinity. Therefore, the intermediate topology channel results for the cylinder master object are not cached.

Step 1310 through step 1350 are repeated for each of the transform and the wave world space modifier 800. Because step 1340 evaluates as false during the processing of the elements effecting the topology channel 1210, no intermediate channel results are cached during these steps. However, at step 1360, the final results for the topology channel are stored in the world space modifier topology channel cache 1467. Thus, the results in the cache 1467 are valid for at least the next ten frames of an animation.

Step 1310 through step 1360 are then executed for all the elements that affect the geometry channel 1210. Note that during the processing of the transform element 230, at step 1340, the interval level 1227 for the next element indicates that the intermediate channel results generated for the next element will not be valid in the next frame of the animation. Thus, step 1350 is executed resulting in the caching of the intermediate channel results in the transform geometry channel cache 1475. Therefore, in the next animation frame, the bound cylinder need only begin evaluating the geometry channel 1220 from the intermediate channel results in the cache 1475 instead of from the cylinder master object 1410 intermediate channel results. Where an object has many modifiers, being able to use the intermediate channel results from a modifier, greatly improves the speed of the system because many calculation are saved. At step 1360, the geometry channel 1220 portion of the derived cylinder representation 1446 is stored in the WSM geometry channel cache 1477.

Note also that the combination of lazy evaluation and the caching in the channels further improve the speed of the system. Lazy evaluation of the channels further reduces the number of unnecessary calculations the entire derived object representation may not be needed to be recalculated in response to a broadcast of changes through a reference from another object. That is, only certain channels may be affected by a set of changes therefore only the caches in these channels need be invalidated.

What is claimed is:

1. A method of modifying the representation of an object in a three dimensional modeling system, comprising the computer-implemented steps of:

- displaying a first three dimensional representation of the object;
- displaying a three dimensional representation of a modifier having a shape indicating an approximate resulting shape of the object when the modifier is applied to the object;

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applying the modifier to the object; and

generating and displaying a second three dimensional representation of the object based on the object and the modifier, wherein the second three dimensional representation of the object is deformed with respect to the first three dimensional representation of the object.

2. The method of claim 1, further comprising the steps of: storing information that defines a plurality of modifiers in a modifier stack, wherein each three dimensional representation of the modifiers has a shape indicating an approximate resulting shape of the object when a particular modifier is applied to the object; and applying the modifiers to the object in the order that the information for each modifier is stored in the modifier stack.

3. The method of claim 2, wherein the application of the modifiers to the object creates a series of three dimensional representations of the object based on the object and the particular modifier that is being applied, wherein each three dimensional representation of the object in the series is deformed with respect to the previous three dimensional representation of the object in the series.

4. The method of claim 2, further comprising the steps of: receiving information that defines an additional modifier, wherein the information that defines the additional three dimensional modifier is not currently stored in the modifier stack; and

storing the information that defines the additional modifier in the modifier stack.

5. A computer-readable medium carrying one or more sequences of instructions which, when executed by one or more processors, causes the one or more processors to perform the method recited in claim 1.

6. A computer-readable medium carrying one or more sequences of instructions which, when executed by one or more processors, causes the one or more processors to perform the method recited in claim 2.

7. A computer-readable medium carrying one or more sequences of instructions which, when executed by one or more processors, causes the one or more processors to perform the method recited in claim 3.

8. A computer-readable medium carrying one or more sequences of instructions which, when executed by one or more processors, causes the one or more processors to perform the method recited in claim 4.

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