3DM

Three-Dimensional Modeler for Head-Mounted Displays

Jeff Butterworth (butterwo@cs.unc.edu)
Marc Olano (olano@cs.unc.edu)
Steve Hench (hench@cs.unc.edu)
Drew Davidson (davidson@cs.unc.edu)

The University of North Carolina at Chapel Hill
Spring, 1991
COMP 145

TABLE OF CONTENTS

Introduction 1
- Getting Started 1
- Modeling 1
- Head-Mounted Displays 1
- Groups 2
- Group Hierarchy 2

Using 3dm 3
- Toolbox 4
- Object Creation and Manipulation 5
  - Triangle Creation Tool 5
  - Mark Tool 6
  - Unmark All Command 6
  - Move/Scale Tool 7
  - Surface of Extrusion Tool 7
- Changing the View 8
  - Fly Tool 8
  - Scale World Tool 9
  - Rotate World Tool 9
  - Default View Command 9
- Undo and Redo 10
  - Undo Command/Redo Command 10
- Hierarchy Editing 10
  - Group Command 10
  - Ungroup Command 11
  - Parent Command 12
  - Merge Command 13
- Clipboard Commands 14
  - Cut Command 15
  - Copy Command 15
  - Paste Command 15
  - Delete Command 15
- Saving and Loading 15
- Color 15
  - Color Selector 15
- Toggle Commands 16
  - Floor On/Off Command 16
  - Magic Carpet On/Off Command 16
- Quit Command 17

Index 18

INTRODUCTION

3dm is a tool for creating complex 3-dimensional (3D) models using Pixel-Planes 4. 3dm gives the user the ability to enter into the artificial world in which the 3D model exists. Once there, the user can use tools to intuitively sculpt a 3-dimensional model.

GETTING STARTED

To execute 3dm, type:

```
/usr/proj/hmd/bin/`hw_os`/3dm
```

The source code is located in:

```
/usr/proj/hmd/src/3dm/
```

MODELING

Modeling has traditionally been a tedious task. At the most primitive level, 3D coordinates are edited by hand and then the model is displayed minutes or hours later as a static image. At a higher level, programs can be written that generate models. However, writing a program requires considerable technical expertise and can still be quite tedious. More sophisticated modeling software exists, such as Sculpt-3D and Wavefront. These programs allow interactive manipulation of the model, which is a level of abstraction above the actual coordinate values, and give the user the ability to work more intuitively and effectively. Unfortunately, these expensive and complicated systems require extensive training to be used effectively.

HEAD-MOUNTED DISPLAYS

The basic reason that modeling is difficult is that the traditional input and output devices are not well suited to manipulation of 3D objects. It is difficult to place an object in the six dimensions of 3D position and orientation with only a mouse and it is equally difficult to get a feel for where the object is with just a 2D screen.

3dm is a logical solution to the difficulties of 3D manipulation because it gives the user the ability to act on 3D models in the user's most familiar environment, 3D space. A head-mounted display supplies stereo vision of the modeling space, which gives the user the visual impression of being in the same room with the object being modeled. The input device for 3dm is a mouse that can convey 3D position and orientation. The mouse completes the environment by giving the user an easy way to grab objects in the modeling space and manipulate them.

An important part of 3dm is the concept of a toolbox. The toolbox contains icons representing tools, which can be grabbed and used. The idea of picking up a

tool and acting upon the model with it is very intuitive and mirrors many of the operations that could be done in a real-world sculpting environment.

GROUPS

The basic entity in the a 3dm model is the *group*. A group contains some geometric primitives and information about how they are interconnected. Currently, this geometry consists only of a triangle mesh. In addition, a group can contain *instances* of other groups. An instance is essentially a copy of another group. Instances are described in more detail later in the manual.

GROUP HIERARCHY

Most models can be separated into groups, which are logical pieces that are coherent subunits. These pieces are usually related spatially. For example, a model of a horse could conceptually be broken into the legs, the body, the neck, and the head. One can envision a hierarchy applied to this set of groups that would organize it into a horse model. As a rule, a group that is moved relative to another one is called the *child* of the second one, which is called the *parent*. In the example, the body is the central group, so it is the parent of all of the other groups. The neck is the only other parent and its single child is the head. This hierarchy is shown below.

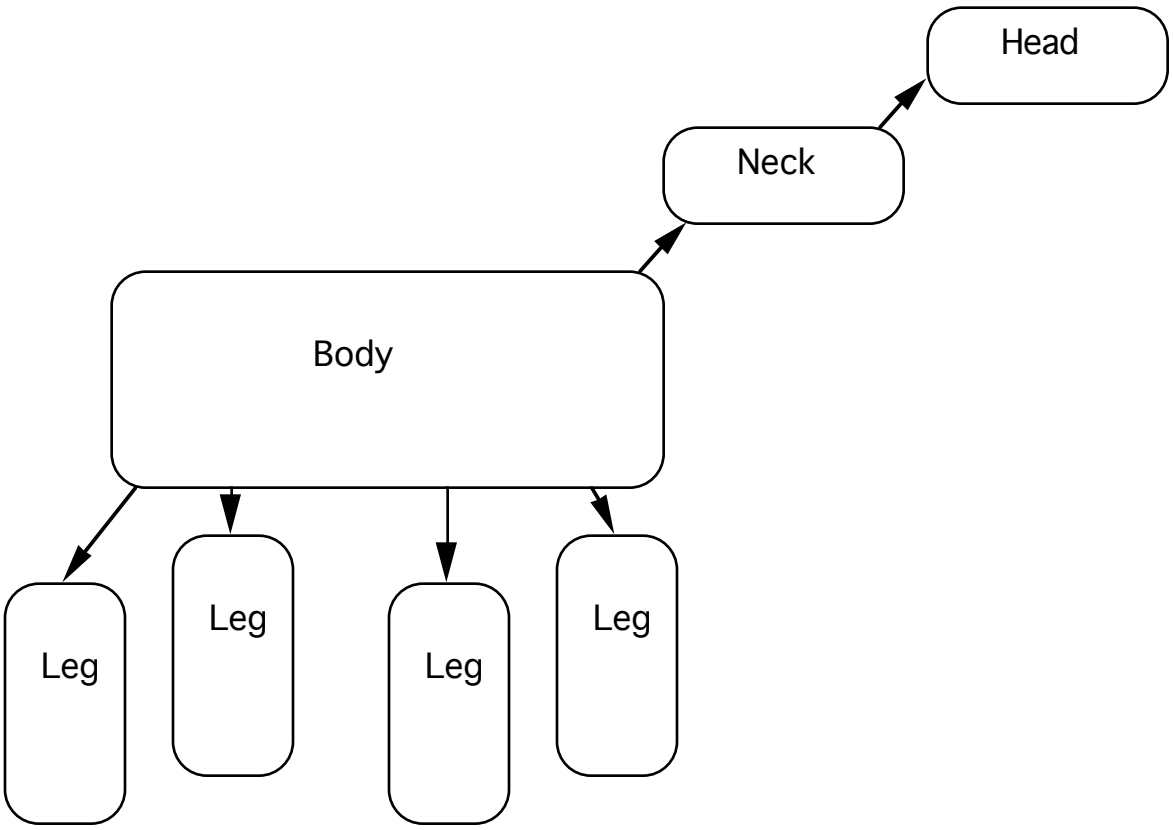


Figure 1: Group Hierarchy

By imposing this organization on the groups, movement of such an articulated model can be greatly simplified. The basic rule of moving hierarchical models is that when a parent moves, all of its children move with it. Thus, the horse's neck can be moved and the head will automatically move with it. The converse is not true: moving the head would not affect the neck.

Another advantage of a hierarchy is that a group can be copied in a special way called *instancing*. Instancing does not actually replicate the polygons that make up an group. Instead, the original group is just displayed in multiple places at once. The advantage of instancing is that there is always just one real description of a group. Editing a group alters all of its instances simultaneously. An example of this is when a horse model has a single foreleg that is instanced twice. By refining the details of one foreleg, the other is automatically changed to match. A diagram showing how the horse model might look with instancing is shown below.

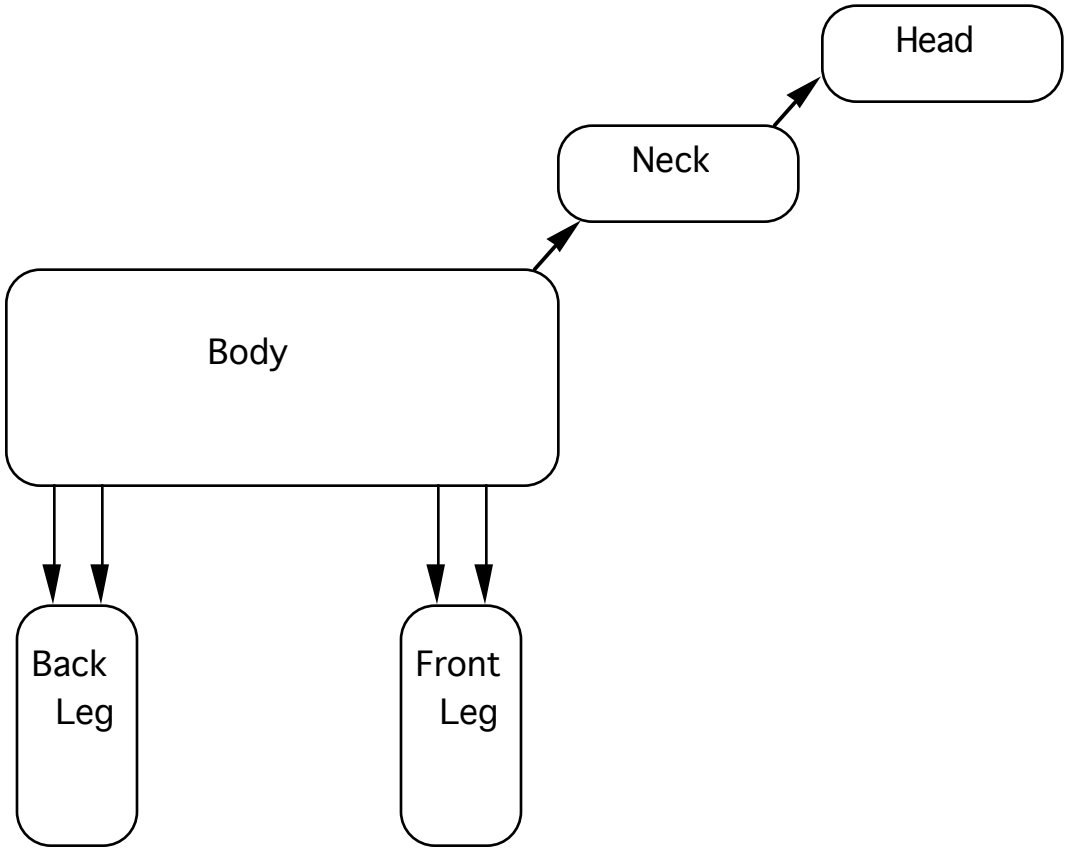


Figure 2: Horse Model with Instancing

USING 3DM

The interface style of 3dm is very similar to the Macintosh 2D drawing program MacDraw. In MacDraw, different modes of operation, known as *tools*, are used to help to avoid unintuitive, complicated commands. In 3dm, as in MacDraw, these modes are chosen by clicking in an icon in a toolbox. The toolbox in 3dm, however,

is an actual object in the virtual world. Tools and commands are represented in the toolbox as icons.

In order for the toolbox to remain easily accessible, it will normally be attached to the user's head and appear connected to the user's belt. By clicking in the upper-right corner of the toolbox, it may be unlocked and moved relative to the room. The toolbox may be locked again to keep it in place relative to the user's head.

TOOLBOX

The toolbox is composed of several cells, most of which contain an icon. Tools and commands may be chosen by clicking in one of the toolbox cells. Tools, whose cells are outlined in blue in the toolbox, represent extended modes of operation. The current tool has a yellow background in its cell.

Commands, whose cells are outlined in green in the toolbox, represent one-time only actions. Some commands are toggle commands, and will change their icon to represent their current state. Unlike tools, commands are generally executed once, immediately. Commands generally operate on vertices, triangles, or groups marked with the Mark tool. If a command only operates on specific type of objects, for example triangles, any "stray" objects, such as marked vertices that do not form complete triangles, are ignored and are not affected. Commands are invoked by clicking on the icon representing the command in the toolbox.

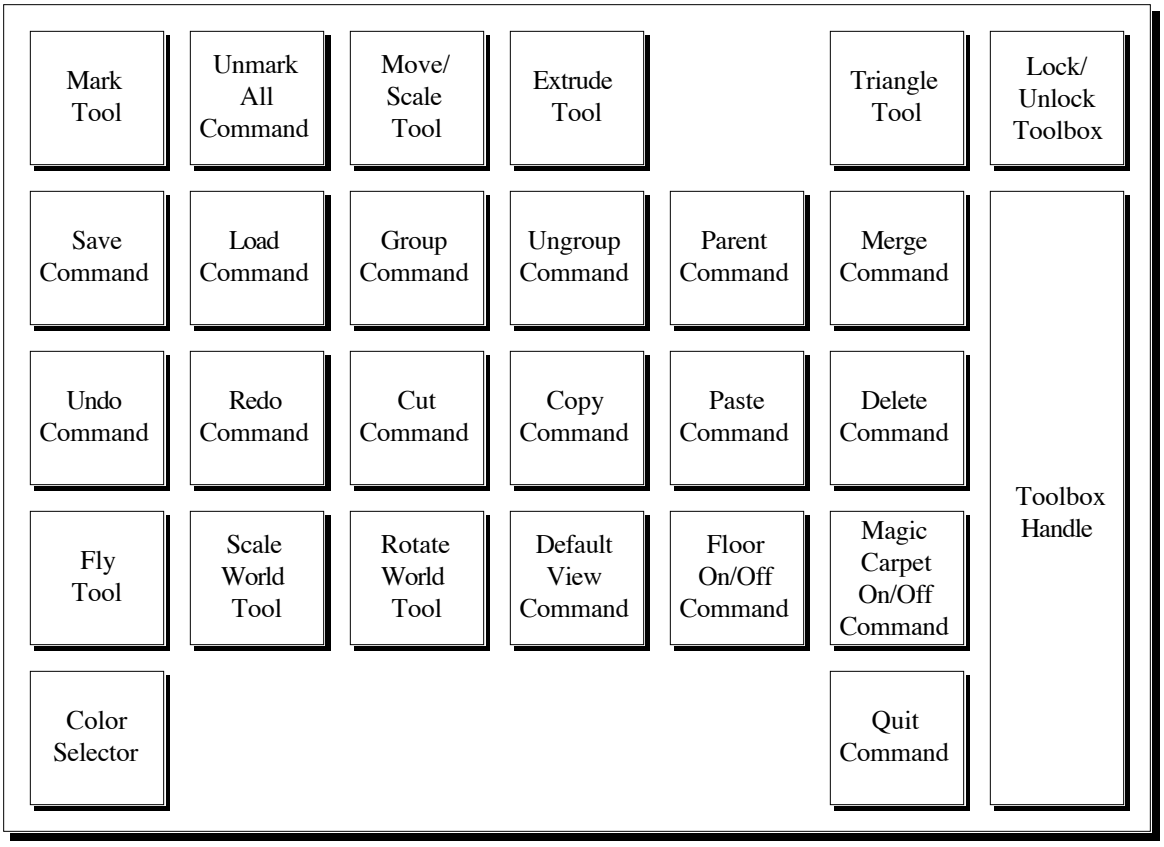


Figure 3. Toolbox

An individual tool is selected by clicking in its icon in the toolbox. As the cursor moves into the toolbox, the cursor will become a red arrow. A cyan square hilite will move around the toolbox with the the hand. If the left mouse button is clicked, the hilited tool becomes the current tool. The tool chosen remains the current tool until another tool is chosen. When a tool is chosen, and the cursor is moved out of the toolbox, the cursor takes on an appropriate shape, to distinguish between the different tools. If the right button is clicked, the name of the tool will be spoken.

In order for the toolbox to remain easily accessible, it will initially be locked to the user's head at about belt level. Wherever the user moves, the toolbox will always be located approximately half a meter below the user's head. The toolbox may be unlocked by clicking in the blue square in the upper-right corner of the toolbox. This square contains a blue circle if the toolbox is currently locked, and contains nothing if the toolbox is currently unlocked. When the toolbox is unlocked, it no longer follows the user's head; instead, it is stationary in the room, and can be walked away from.

The toolbox, whether locked or unlocked, is unaffected by the Fly, Scale World tool, or Rotate World tools. These tools do not affect the toolbox position relative to the user. In other words, it is impossible to "fly away from" the toolbox. However, if the toolbox is unlocked, it is possible to walk a few meters away.

OBJECT CREATION AND MANIPULATION

TRIANGLE CREATION TOOL

Models in 3dm are made entirely of triangles. Triangles are created with the Triangle Creation tool.

To create a triangle, its three vertices must be defined. When using the Triangle tool, click the left mouse button to define vertices. Lines will "rubber band" between the click locations and the current mouse position to aid in defining precise triangles. After the third click, a triangle will appear.

Triangle strips can be rapidly created with the right mouse button. The right mouse button creates a triangle using the two most recently created vertices. Thus, three clicks with the left button will create a triangle, and every click after that with the right button will create a triangle based on the previous two vertices specified.

In order to use previously defined vertices in a new triangle, "snapping" is possible. When the cursor is moved near a vertex, a cyan wire-frame cube with a small star in the center appears around it indicating that a button press will use that vertex rather than creating a new one. This ability to reuse vertices makes it possible to exactly connect triangles without a crack appearing between them.

TRIANGLE CREATION TOOL SUMMARY

EVENT	LEFT BUTTON	RIGHT BUTTON
Press (0-1 Vertices Created)	Create Vertex	Create Vertex
Press (2 Vertices Created)	Complete Triangle	Complete Triangle
Press (>2 Vertices Created)	Start New Triangle	Complete Triangle

MARK TOOL

The Mark tool is used to mark vertices and entire groups that have been created with other tools or read in from a file. Marked objects may be moved or scaled with the Move/Scale tool. Marked objects may be cut, copied, pasted, or deleted with the Cut, Copy, Paste, and Delete commands respectively. Marked objects may be made into a group with the Group command, ungrouped with the Ungroup command, parented with the Parent command, and merged into a group with the Merge .

Marked objects may be extruded with the Extrude tool or revolved to create a surface with the Surface of Revolution tool. Note, however, that these tools can be used to mark edges as well as vertices, triangles, and groups (see Surface of Extrusion and Surface of Revolution tools, below).

When the cursor moves near a vertex in the model, a cyan wire-frame cube with a small star in the center will appear around the vertex. When a vertex is hilited in this way, clicking the left mouse button marks that vertex. If the vertex is already marked, clicking the left button will unmark the vertex. A marked vertex has a small blue pyramid displayed around it.

If the cursor is near a hilited vertex, clicking the right mouse button "moves up the hierarchy" of groups. For example, if a single vertex of a group defined as a chair is marked, clicking the right button while the mouse is close to the marked vertex will mark the entire chair. A marked group has a blue wireframe box displayed around it.

Clicking the left mouse button and dragging temporarily creates a cyan wire-frame box with opposite corners at the initial click point and the current mouse location. When the mouse button is released, all of the vertices within the wire-frame box are marked and the box disappears.

When an object is marked, any instances of that object are also immediately marked in a way known as "shadowed selection." Objects that are shadow-selected do not appear marked, but if the original object is moved or modified, the shadow-selected instances are immediately updated (see Hierarchy Editing, below). If a shadow-selected object is marked it ceases to be shadow-selected, and the previously marked instance becomes shadow-selected and ceases to be marked.

MARK TOOL SUMMARY

EVENT	LEFT BUTTON	RIGHT BUTTON
Click in Marked Vertex	Unmark Vertex	Mark Up One Level
Click in Unmarked Vertex	Mark Vertex	Mark Up One Level
Drag in Space	Mark Vertices in Box	

UNMARK ALL COMMAND

The Unmark All command is used to unmark all the objects. Select this command and all of the displayed marks will disappear.

MOVE/SCALE TOOL

The Move/Scale tool is used to move marked objects relative to the world and each other. Triangles may be deformed by moving one or two of their vertices. Marked objects may be scaled about any arbitrary point.

Dragging with the left mouse button held down moves all marked objects the same way the mouse is being moved, including both translation and rotation. Only the marked vertices and bounding boxes will actually appear to move while the button is being held down. The new position of the triangles will not be visible until the drag is completed. When the left button is released, the object will appear in the new position.

Dragging with the right mouse button held down scales all marked objects. The point initially clicked will be the point the objects are scaled from. When the right button is pressed, a cyan wire frame box will appear, with a small cyan star at the origin of scaling (that is, the point where the mouse was initially pressed). Dragging up with the right mouse button held down scales the marked objects up, dragging down scales the marked objects down. Only the the marked vertices and bounding boxes will actually appear to move while the button is being held down. The new position of the triangles will not be visible until the drag is completed. When the right button is released, the object will appear with their new scaling.

The toolbox will temporarily disappear while objects are being moved or scaled.

MOVE/SCALE TOOL SUMMARY

EVENT	LEFT BUTTON	RIGHT BUTTON
Click & Drag	Move Selected Objects	
Click & Drag Up		Scale Selected Objects Up
Click & Drag Down		Scale Selected Objects Down

SURFACE OF EXTRUSION TOOL

The Surface of Extrusion tool allows creation of relatively free-form surfaces by creating triangles between two sets of edges. First the line segments that form base for the extrusion are given. Then a copy of this base is dragged into place with the mouse. Between the corresponding edges on the two copies, a surface is created. Dragging again creates a surface between the second copy and a third, so repeated extrusion can be performed along a complex path. The base for the extrusion can be made from any arbitrary collection of line segments. These segments are not constrained to lie in a plane, to be connected, or to coincide with existing edges in the database. The new position of the extrusion base is also not constrained in any way by the position of the original. Admittedly, this makes it is possible to twist the relative positions to create a meaningless jumble of triangles, but it also makes it possible to sweep out arbitrary curved paths.

When the extrusion tool starts, the extrusion base is set to use all edges between marked vertices in the database. This base can be added to (or one created from scratch) inside the extrusion tool itself. The unattached edges created inside the extrusion tool are not physically part of the model, but serve only as a step in defining the surface. After using the extrusion tool, these temporary edges

disappear, though the surfaces they helped define will remain. The creation of these temporary edges is analogous to the creation of triangles in the triangle creation tool. Each click of the left button adds an edge to the extrusion base. The edge that will be added is shown with a rubber-band line. Clicking the right button resets the starting point of the rubber-band line to the current position without adding an edge to the extrusion base.

The actual extrusion is performed by holding down the left button and dragging the marked extrusion base to a new location and orientation. When the button is released, the surface is created. The leading edge of the extrusion is automatically marked so the operation can be repeated. An example of the extrusion operation can be seen in figure 3.

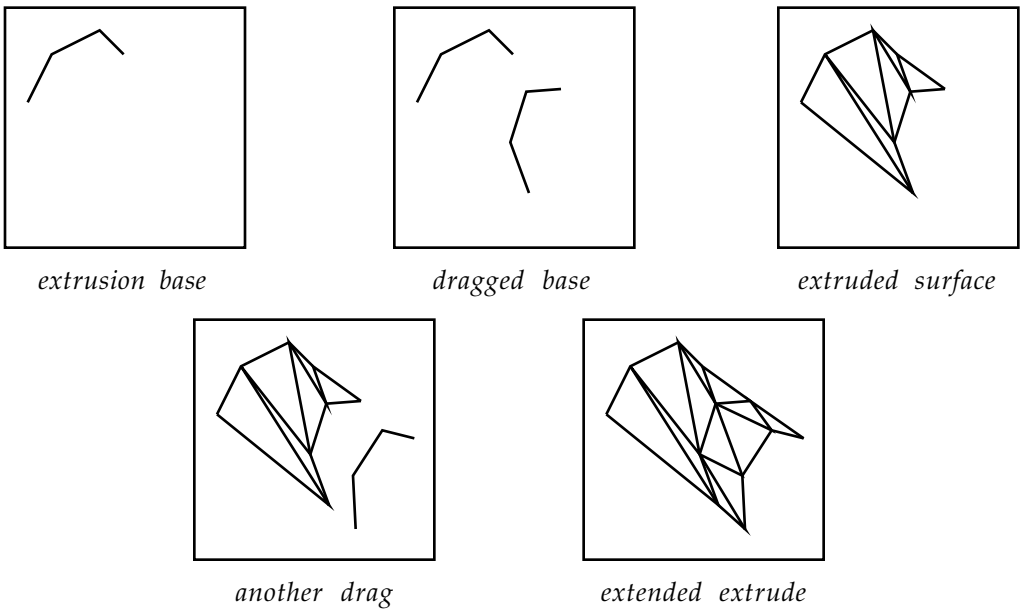


Figure 4. Extrusion operation

SURFACE OF EXTRUSION TOOL SUMMARY

EVENT	LEFT BUTTON	RIGHT BUTTON
Click	Add Edge to Extrusion Base	Move Starting Point of Edge
Click, Drag, & Release	Create Extruded Surface	

CHANGING THE VIEW

FLY TOOL

The Fly tool is used to fly around the world. When the Fly tool is chosen, the cursor appears as an airplane. When the left button is held down, the user moves through the world in the direction the airplane points. While the right button is being held down, the user moves through the world in the opposite direction the airplane points.

The Fly icon appears as a yellow-orange airplane.

The toolbox will temporarily disappear while flying is taking place, and will reappear when the mouse button is released.

The Default View command can be used to return to the floor after flying around.

FLY TOOL SUMMARY

EVENT	LEFT BUTTON	RIGHT BUTTON
Hold Down Button	Fly Forward	Fly Backward

SCALE WORLD TOOL

The Scale World tool is used to scale the model and floor relative to the user. When the Scale World tool is chosen, the cursor becomes two red arrows pointing at each other. When the left button is held down, the world is scaled up relative to the user; that is, the floor and model get bigger. The objects in the model are not actually scaled up; the Move/Scale tool is used to scale marked objects.

The Scale World icon appears as four red arrows pointing outward.

The toolbox will temporarily disappear while the world is being scaled, and will reappear when the mouse button is released.

The Default View command can be used to return to the default scaling after scaling the world with the Scale World tool.

SCALE WORLD TOOL SUMMARY

EVENT	LEFT BUTTON	RIGHT BUTTON
Hold Down Button	Scale World Up	Scale World Down

ROTATE WORLD TOOL

The Rotate World tool is used to rotate and translate the model and floor relative to the user. When the Rotate World tool is chosen, the cursor becomes three orthogonal green planes. When the left or right button is held down, the world is rotated and translated relative to the hand; it is as if the the user has grabbed the entire universe. The objects in the model are not actually translated or rotated; the Move/Scale tool is used to move marked objects.

The toolbox will temporarily disappear while the world is being rotated, and will reappear when the mouse button is released.

The Default View command can be used to return to default position and orientation of the world after rotating or translating it with the Rotate World tool.

ROTATE WORLD TOOL SUMMARY

EVENT	LEFT BUTTON	RIGHT BUTTON
Drag	Rotate & Translate World	Rotate & Translate World

DEFAULT VIEW COMMAND

The Default View command is used to return to the default translation, rotation, and scaling of the world, as when 3dm is first started up. This command

immediately nullifies the effect of any previous uses of the Fly, Scale World, and Rotate World tools.

The Default View command is represented by an eye icon in the toolbox.

UNDO AND REDO

UNDO COMMAND/REDO COMMAND

Since mistakes are a common fact of life, 3dm has a powerful undo capability. The Undo command can back up one change at a time, all the way to the start of the session. The undo feature itself is one of the most dangerous in the model, so a redo function is also provided. The Redo command puts the changes back, one at a time, until the point where the first undo in a series of undo's was used. To help in remembering what a particular undo or redo will change, the icons to reflect what their action will be. The undo icon is a red circle with a slash through it, superimposed over the icon for the tool or command that will be undone, while the redo icon is a green circle superimposed over the icon for the tool or command that will be redone.

HIERARCHY EDITING

The following set of commands allow the user to manipulate the hierarchy of groups, rather than simply the data contained within a group. If a triangle is given a new parent it remains in the same visible location, but its interaction with the groups in the scene has changed.

Care must be taken when groups have more than one instance. If an object is removed from its parent it will affect all instances of the parent, and the shadow-selections may vanish even if the object was not deleted.

If at any point while using these commands a group is modified so that it has no triangles or children, it is removed from the hierarchy since there is no longer any way to refer to it.

Undo is supported for all of these commands.

GROUP COMMAND

The Group command removes any marked groups and triangles from their parents, and brings them together into a new group at the top of the hierarchy. This command is how newly created triangles can be formed into a group, and is one way to specify child groups.

As an example, assume that the triangles for a chair and table have already been created and reside at the topmost, initial level of the hierarchy. To form a group to represent the chair, mark all the triangles forming the chair and select the Group command in the toolbox. Similarly, a group can be created containing all of the triangles forming the table. If the chair and table groups are then marked and the Group command used once again, a third group is created with the two previous groups as its children.

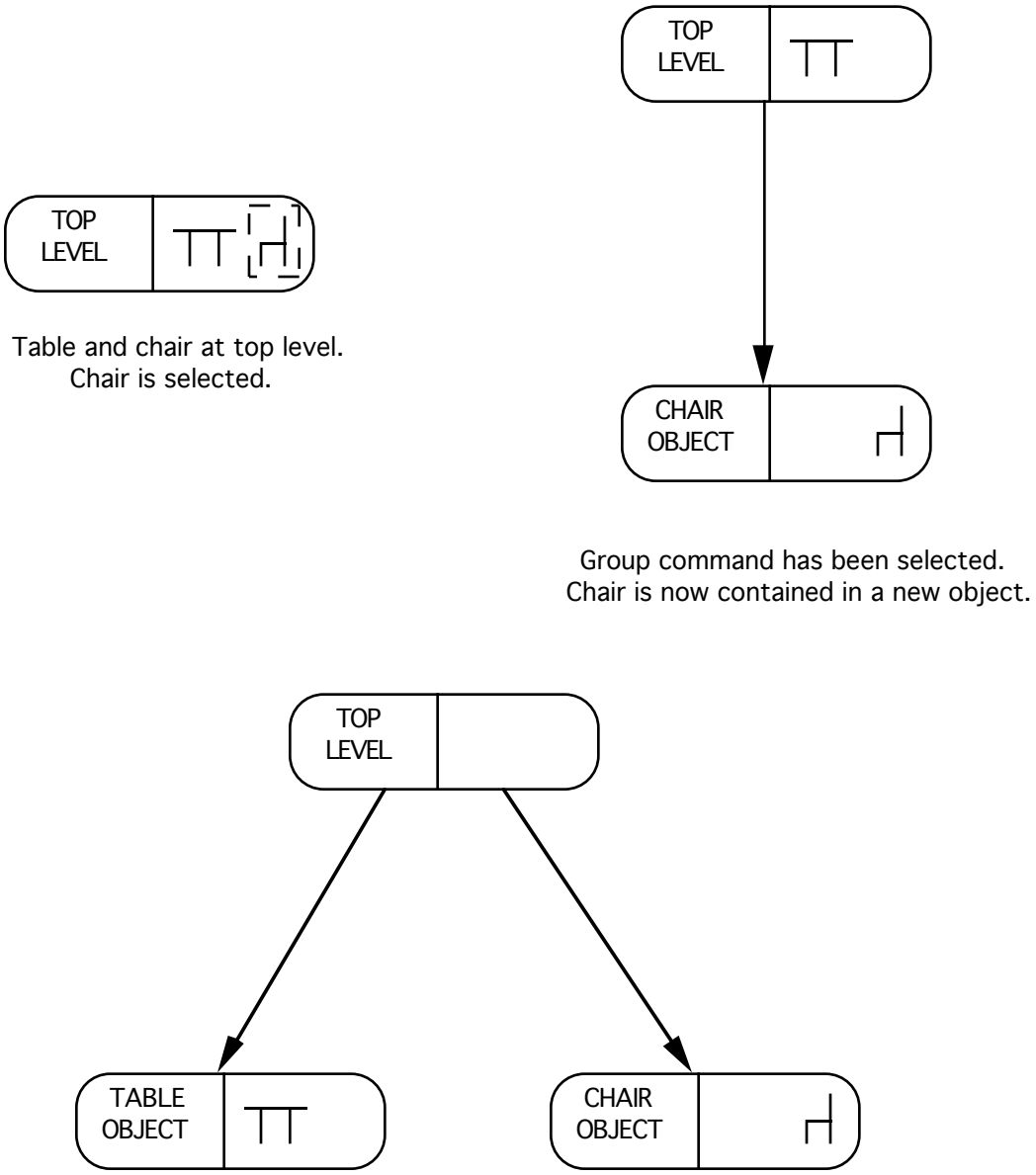


Table and chair at top level.
Chair is selected.

Group command has been selected.
Chair is now contained in a new object.

Table and group command have been selected.
Table is now contained in a new object.

Figure 5. Grouping

If marked and unmarked triangles are connected the unmarked triangle is untouched and the marked triangle is moved to its new location in the hierarchy.

UNGROUP COMMAND

The Ungroup command removes any marked groups and triangles from their parents, and places them at the top of the hierarchy. Unlike the group command, this command does not create a new group, and can be used to selectively pick out objects within existing groups. If everything in a group is marked and Ungrouped, the group is deleted and all of its triangles and children are placed at the top level.

If marked and unmarked triangles are connected the unmarked triangle is untouched and the marked triangle is moved to its new location in the hierarchy.

PARENT COMMAND

The Parent command assigns a new parent to any marked triangles and groups. After you have marked the objects you wish to have a new parent, select the Parent command in the toolbox. The cursor will change to show that the parent command is still in effect and that a parent must be chosen. Choosing a parent is similar to marking a group with the Mark tool

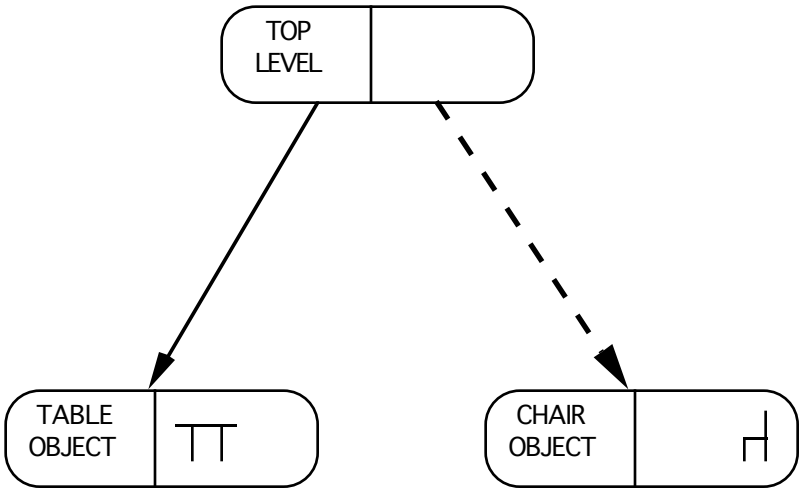
When the cursor moves near an vertex in the model, a cyan wire-frame cube with a small star in the center will appear around the vertex. When a vertex is hilited in this way, clicking the left mouse button selects the group containing the vertex and the command is ended.

If the cursor is near a hilited vertex, clicking the right mouse button "moves up the hierarchy" of groups and does not end the command. For example, if a single vertex of a group defined as a chair is marked, clicking the right button while the mouse is close to the marked vertex will mark the entire chair. A marked group has a green wireframe box displayed around it. Clicking the left mouse button ends the command and the marked group is used as the new parent.

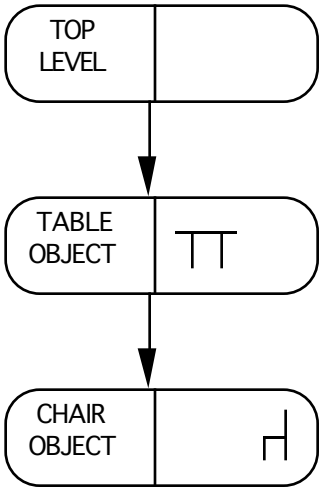
PARENT COMMAND SUMMARY

EVENT	LEFT BUTTON	RIGHT BUTTON
Click in Vertex	Select Group and End Command	Select Up One Level

For example, assume we have a table group and a chair group. To make the chair a child of the table, mark the chair and select the Parent command. Then, select the table to make it the parent.



Chair object has been selected.



Parent command and table have been selected.
Table is now the parent of the chair.

Figure 6. Parenting

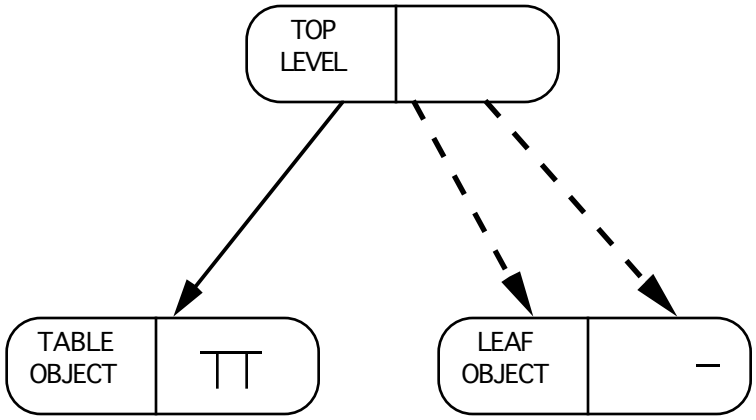
If marked and unmarked triangles are connected the unmarked triangle is untouched and the marked triangle is moved to its new location in the hierarchy.

MERGE COMMAND

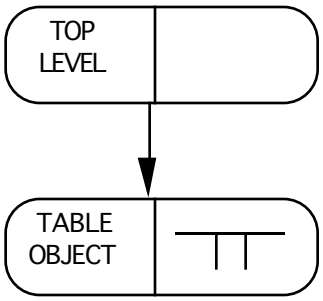
The Merge command assigns a new parent to the children of any marked groups and merges their triangles into the new parent. After you have marked the groups you wish to merge, select the Merge command in the toolbox. The cursor will change to show that the Merge command is still in effect and that a parent must

be chosen. Choosing a parent with the Merge command is exactly the same as choosing one with the Parent command.

For example, assume we have the leaves of a table as groups separate from a table group. To add the leaves to the table group, mark the leaves and select the merge command. Then, select the table to make it the parent. The triangles forming the leaves are joined with those forming the parent and the leaf groups are removed.



Both leaf objects have been selecte



The leaves have been joined to the tab
The leaf objects no longer exist.

Figure 7. Merging

Anything marked that is not an object is ignored.

CLIPBOARD COMMANDS

The Clipboard is a temporary holding place for triangles and instances for the four commands below. When new material is added to the Clipboard the previous contents vanish. The Clipboard is not saved when you quit the program.

CUT COMMAND

The Cut command removes any marked triangles and groups and places them in the Clipboard.

If a triangle is marked for cutting and it is connected to an unmarked triangle the unmarked triangle is untouched and the marked triangle is placed in the Clipboard.

COPY COMMAND

The Copy command puts a copy of any marked triangles and groups in the Clipboard. The marked material is unaffected.

PASTE COMMAND

The Paste command puts a copy of the contents of the Clipboard at the top level of the hierarchy. The copied material is automatically marked so it is ready to be moved where you wish.

DELETE COMMAND

The Delete command deletes any marked triangles and groups and *does not* place them in the Clipboard. Any material currently in the Clipboard is unaffected.

If a triangle is marked for cutting and it is connected to an unmarked triangle the unmarked triangle is untouched and the marked triangle is destroyed.

SAVING AND LOADING

The Save and Load commands provide the capability to use models in other programs or to save work in progress and return to it later. The files are saved in a format compatible with Pixel-Planes PPHIGS archive format. This format can be read by a PPHIGS application after it has been converted to a binary form with the program **`makearch`**. Since 3dm does not support all of the features of PPHIGS, most PPHIGS archive files cannot be read by 3dm without modification. More details on the file format requirements can be found in the implementation document, but the basic changes are summarized here. The top level structure must be named `TDM_Model`. Only simple polygons with three vertices can be used. The color of the triangles can be changed with the "`polygon color`" command. In a single structure, the structure executions should come after all of the triangles. And any structure execution must be immediately preceded by a transformation matrix (even if its just the identity) with the `Replace` option.

COLOR

COLOR SELECTOR

The Color Selector is used to change the color of parts of the model. When a color is chosen, marked triangles immediately become the chosen color. The chosen color also becomes the current color. All new triangles created with the Triangle

Creation tool, the Surface of Extrusion tool, and the Surface of Revolution tool will appear in the current color.

To choose a color, press and hold the button in the Color Selector cell. The toolbox will be replaced with the color selector as long as the mouse is held down. To select a color, drag the mouse to the new color. The old and new colors will appear in a rectangle above the grid of colors. The new color changes as the hand is dragged around the grid of colors. When the new color is the desired color, release the mouse button to choose it as the current color.

The Color Selector icon appears as a square that is the same color as the current color. The default current color is white.

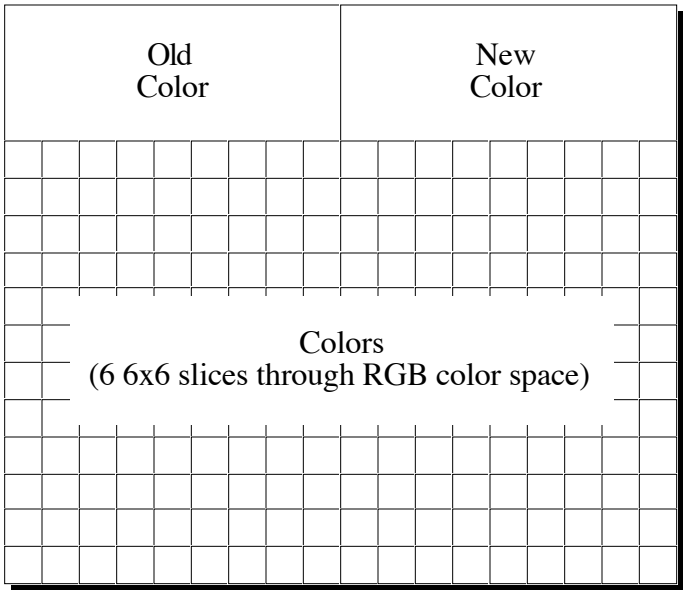


Figure 8: Color Selector

TOGGLE COMMANDS

FLOOR ON/OFF COMMAND

The Floor On/Off command is used to turn off the floor, if the floor gets in the way of building a model. The Floor On/Off command is represented by a miniature floor icon in the toolbox. When the command is Floor Off (that is, when the floor is currently on), the icon has a red X over it. When the command is Floor On (that is, when the floor is currently off), the icon does not have a red X over it.

MAGIC CARPET ON/OFF COMMAND

The Magic Carpet On/Off command is used to turn off the magic carpet, if the magic carpet gets in the way of building a model. The Magic Carpet On/Off command is represented by a miniature magic carpet icon in the toolbox. When the command is Magic Carpet Off (that is, when the magic carpet is currently on), the icon has a red X over it. When the command is Magic Carpet On (that is, when the magic carpet is currently off), the icon does not have a red X over it.

QUIT COMMAND

The Quit command immediately quits 3dm. The current model will not be saved unless it is explicitly saved with the Save command before quitting.

The Quit command icon looks like a red octagon with a white X over it.

INDEX

archive format 15
base 7
Clipboard 14, 15
Clipboard Commands 14
    Copy 15
    Cut 15
    Delete 15
    Paste 15
Color 15
Color Selector 15, 16
commands 4
    clipboard commands 14
    Copy 6, 15
    Cut 6, 15
    Default View 9
    Delete 6, 15
    Floor On/Off 16
    Group 6, 10
    Hierarchy Editing 10
    Load 15
    Magic Carpet On/Off 16
    Merge 6, 13
    Parent 6, 12
    Paste 6, 15
    Quit 17
    Save 15
    toggle 4
    Undo 10
    Ungroup 6, 11
    Unmark All 6
Copy command 6, 15
cursor 5
Cut Command 15
Cutc command 6
Default View command 9, 10
Delete command 6, 15
edges 6, 7
Extrude tool 6
Extruded Surface 8
extrusion 7
extrusion base 7, 8
Floor On/Off Command 16
Fly 5
Fly Tool 8, 10
geometry 2
group 2, 10
Group command 6, 10
group hierarchy 2
    children 2, 13
    parents 2
groups 2, 4, 6, 10, 11, 14
head-mounted display 1
head-mounted displays 1
hierarchical models 3
hierarchy 2, 6, 10, 11, 12
Hierarchy Editing 6, 10
icons 1, 4
input device 1
instances 2, 3, 10
instancing 3
Load Command 15
MacDraw 3
Macintosh 3
Magic Carpet On/Off Command 16
makearch 15
Mark tool 4, 6, 12
marked 8
marked vertices 7
marking objects 6
Merge command 6, 13, 14
modeling 1
modes 3, 4
Move/Scale Tool 6, 7, 9
Object Creation and Manipulation 5
objects
    moving 7
objects scaling 7
Parent Command 12, 14
Paste Command 15
Pastecommand 6
Pixel-Planes 1, 15
polygon color 15
PPHIGS 15
Quit command 14, 17
Redo Command 10
Replace 15
Rotate World tool 5, 9, 10
Save Command 15, 17
Saving and Loading 15
Scale World tool 5, 9, 10
Sculpt-3D 1
snapping 5
structure execution 15
Surface of Extrusion tool 6, 7, 16
Surface of Revolution tool 6, 16
TDM_Model 15
toggle commands 4, 16
toolbox 1, 3, 4, 5, 9, 16
    locking 4, 5
tools 1, 3, 4

Fly 8, 10
Fly tool 5
Mark 6, 12
Move/Scale 6, 7, 9
Rotate World 5, 9, 10
Scale World 5, 9, 10
Surface of Extrusion 7, 16
Surface of Revolution 6, 16
Triangle Creation 5, 16
Triangle Creation Tool 5, 15
triangle strips 5
triangles 4, 5, 6, 7
Undo Command 10
Ungroup Command 11
Unmark All Command 6
vertices 4, 6
Wavefront 1