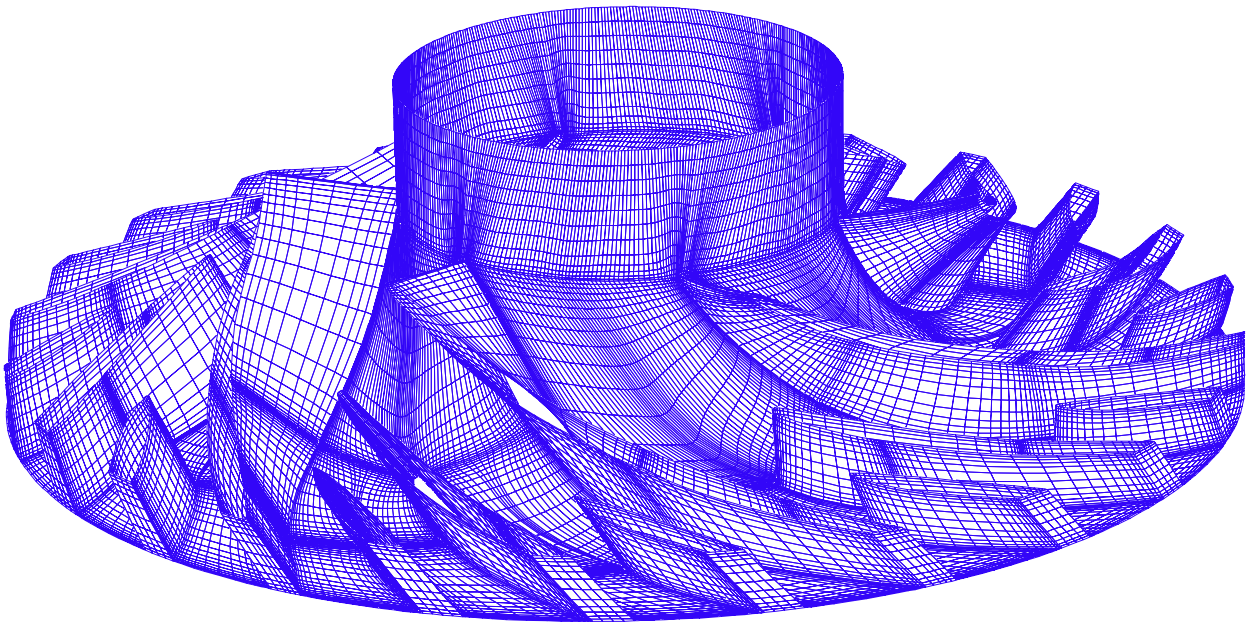
True*Grid*®

"A quality mesh in a
fraction of the time."



Version 2.1

A Tutorial

Table of Contents

An Overview

Introduction to True*Grid*®

True*Grid*® is a general purpose tool for creating a multiple-block-structured mesh. Although the beginning of this Tutorial provides some introductory information, the new user is strongly advised to read the first 2 chapters of the User's Manual before proceeding with this document.

The processes of creating a mesh and creating geometry are separated within **True*Grid*®**. Surfaces and curves may be created internally or imported from a CAD/CAM system via an IGES file. A block mesh is then created and molded to the shape of the geometry.

Making a mesh with **True*Grid*®** is analogous to sculpting: A block mesh is created using the **block** command. Pieces of the block mesh are removed so that its topology matches that of the object to be meshed. Portions of the mesh are moved, positioned along curves, projected to surfaces, etc. Interpolation, smoothing, and zoning requirements are used to fine-tune the mesh. Parts created separately are glued (merged) together automatically by specifying a tolerance.

True*Grid*® is based on a powerful technique known as the **projection method**. The projection method allows faces, edges, and nodes of the mesh to be directly placed on surfaces. Similarly, edges and nodes of the mesh can be placed along curves. In this sense, **True*Grid*®** is a constraint-based mesh generator.

Additionally, if **True*Grid*®** is required to place two faces of the mesh sharing a common edge onto two different surfaces, then it will **automatically place the shared edge on the intersection of the two surfaces**. There is no need to construct the intersection curve of two surfaces; **True*Grid*®** will find the intersection curve automatically. Likewise, a vertex required to be on three surfaces will be placed at a common intersection point of all three surfaces.

Other notable features of **True*Grid*®** include:

1. **True*Grid*®** is completely **interactive**.
2. Any number of **commands can be deactivated and reactivated**.
3. **True*Grid*®** is a WYSIWYG (What you see is what you get.)-- **the actual mesh is shown at all times**.
4. The most frequently used **mesh generation commands can be performed using the mouse**.
5. **The mesh can be interactively refined**.
6. **True*Grid*®** produces **clean session files** that can be **easily edited, rerun, and interrupted** (for interactive mesh editing).

The Phases of True*Grid*®

True*Grid*® behaves in different ways depending on what commands have been issued so far. When the command `tg` is first issued, a text and menu window appears on the screen in the upper left corner. The initial title of this window is *Control Phase*. The title of this particular window will always indicate the current phase of **True*Grid*®**. Because the current phase depends on the commands issued, the text and menu window title changes depending on the commands issued interactively and/or read from a batch file.

The Control Phase, the initial phase of the code, is where output options are chosen, material models defined, geometry created, and where parameters governing the final mesh output file are set. No graphical capabilities are available in the Control Phase.

The Part Phase is entered as soon as a block mesh is created using either the `block` or `cylinder` command. Three new windows appear in the Part Phase: the *Computational* Window (used for displaying logical blocks of the mesh), the *Physical* Window (used for displaying the actual mesh and any geometry), and the *Environment* Window (used to determine what is in a graphics window, how it is displayed, and how it can be manipulated using the mouse). It is in the Part Phase where the mesh is constructed by positioning, projecting, deleting, zoning, refining and smoothing parts of the mesh (as well as by performing other functions). Boundary conditions for a part are also specified in the Part Phase.

The Merge Phase is where parts are assembled into one model by merging, i.e., gluing, nodes together that are within a specified tolerance of each other. Only the *Computational* window of the Part Phase is missing. Both the *Physical* and *Environment* windows are present in the Merge Phase. It is in the Merge Phase that the mesh output file is written. There are features available in the Merge Phase to view boundary conditions, to diagnose the condition of the mesh, and to view the highest-quality images of the mesh and geometry.

As **True*Grid*®** evolves, the need for the Control Phase diminishes. Eventually, the Control Phase will be eliminated in favor of the Merge Phase. This will make graphics capabilities available at all times within **True*Grid*®**. Most functionality once available only in the Control Phase has already been incorporated into the Merge Phase.

Menus,

Dialogue Boxes,

and Help

Text/Menu Window, Menus, Dialogue Boxes and Help

The Main Menu

Run **True*Grid*®** with no input file using the command

```
tg
```

A single window appears in the upper left corner of the screen. The main menu of **True*Grid*®** appears in this text/menu window. This text/menu window has a title indicating the current phase of the code (either *Control Phase*, *Part Phase*, or *Merge Phase*). Commands can be issued from this window, and any output such as warnings or error messages is directed to this window.

Because of the limited screen space, the text/menu window is not particularly large. This leaves room for other windows that appear in the other phases of the code. Consequently, when there is output from **True*Grid*®** to the user, the menu automatically disappears and the text portion of the text/menu window is enlarged to fill the window. For example, enter the illegal command

```
junk
```

on the command line. A message is issued indicating that `junk` is an illegal command. Notice that the menu is no longer visible.

To bring the menu back, either press the Enter key or press the **right mouse button** (3-button mouse) in the text/menu window, or press the **middle mouse button in the scroll bar area** of the window.

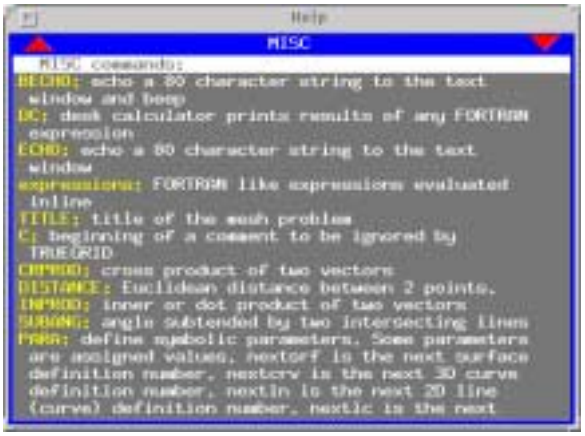
To expand the text area to cover the window and remove the menu, press the **upward-pointing arrow** appearing on the right of the text/menu window, or press the **Page Up** key or the **Up Arrow** key on the keyboard while the cursor is in the text window. Any of these actions indicate to **True*Grid*®** that you wish to view more of the previous text. In such cases, the text area expands to fill the window, thereby making more of the previous text visible. **To scroll** through the text, either use the **Page Up**, **Page Down**, **Up Arrow** or **Down Arrow** keyboard keys, or use the **scroll bar**. Pressing the left mouse button on the arrows above the scroll bar moves text by pages. Pressing the middle mouse button on the arrows moves the text by lines.

Getting Help For a Main Menu

In the main menu area of the text/menu window there are two **grey buttons**, the **HELP** button and the **EXIT** button.

Press the **EXIT** button with the left mouse button to **quit True*Grid*® without confirmation**.

Press the **HELP** button to activate the help system. Normally, pressing the left mouse button on an entry of the main menu causes a submenu to appear. However, when the **HELP button is on**, pressing the **left mouse button** on a main menu entry **calls up a Help Window** containing information about all the commands in the given category.



The **Help Window** contains a title bar with scroll arrows as required. Pressing the **left mouse button scrolls by page**. Pressing the **middle mouse button scrolls by line**. The Page Up, Page Up, Up Arrow and Down Arrow keys can also be used for scrolling.

All **command names** in the category are **highlighted in yellow**. A description of the options for each command and their purposes is stated.

Pressing the left mouse button on another category of the main menu replaces the contents of the current help window with information about the new category. This feature allows for easy browsing through all categories of the menu.

To kill the Help Window, either use window manager pop-ups or **turn the HELP button off**.

Sub-Menus

Submenus contain a list of all the commands in a main-menu category. One uses a submenu to **access detailed help or a dialogue box for each command** in the main-menu category.

A submenu is viewed by pressing the left mouse button on a category of the main menu

while the HELP button is off.

Each submenu contains two **grey buttons**: a **MAIN MENU** button and a **HELP** button. Press the MAIN MENU button to return to the main menu. The HELP button of a submenu works the same as that of the main menu. Each submenu also contains as its first entry a **red** button which indicates the name of the current submenu. *The red button is not an active button.*

Getting Help For a Submenu Item

When the mouse is moved onto a command button in the submenu, a bar appears above the text/menu window with a short description of that command.

The help system works the same as for the main menu, but the Help Window for a command in a submenu is far more specific.

The **first part of the help** for a command is in white with black print. This part **is extracted from the main menu help**.

The **second part of the help** contains a **complete syntax** for the command. All **literal options are in upper-case letters**. Other strings (especially those containing underscores) are meant to describe the type of data to be enter. **Semicolons should be regarded as literal**.

Dialogue Boxes

Dialogue boxes are available for every **True*Grid*®** command. **To obtain a dialogue box** for a particular command, move to the submenu containing that command, and **press the left mouse button on the command name**. (Make sure the HELP button is off.)

True*Grid*® dialogue boxes can contain incredibly complex decision trees, especially for commands used to set options for output to a particular simulation code.

True*Grid*® dialogue boxes may contain **input field**s and option lists as well as descriptions and/or titles for such.

An input field consists of an optional description (in white print), prompts (in light grey print), and cursor boxes (initially green).

There may be many input fields within a dialogue box. The current active field (the one to which text input is directed) is always displayed with a filled green cursor. The other active cursors are hollow green cursors.

There are three types of input fields:

1. Fields for entering a single number,

2. Fields for entering a list of numbers,

3. Fields for entering general strings.

In the first two cases, **input is checked as it is entered**. **Characters that would create an invalid string are ignored**. Furthermore, if just one number is required, then **True*Grid*®** will not allow a second number to be entered into that field.

Moving the Cursor in a Dialogue Box

The active cursor can be repositioned to another character of the current field, or to another field entirely **using the left mouse button**. Press the left mouse button on the prompt itself to position the cursor at the end of the input field. **Alternatively, press RETURN to move the cursor to the next available field**.

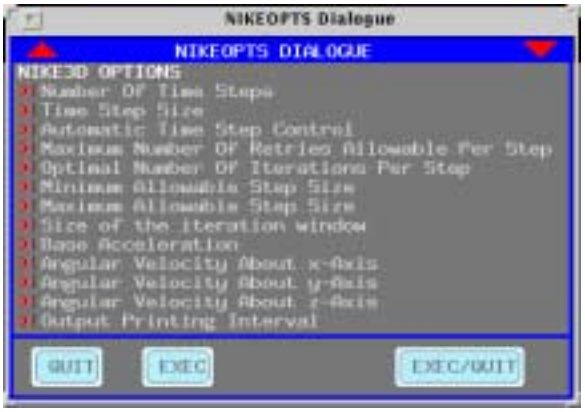
If the current field is empty, the cursor can always be moved from the field. However, **if the current field is non-empty and is not complete**, then **True*Grid*® will not allow the user to move the cursor** from the current field. For example, **1.0e-** can be entered, but **is not complete**. **True*Grid*®** informs the user of such problems **by turning the active cursor blue**. The user must correct the problem before the cursor can be moved to another field. The user can use the mouse to move the cursor to a previous character of the current field. The backspace can be used to delete a previous character. Or, **CTRL+X** can be used to **delete the character beneath the cursor**.

When the user presses the ENTER key to end the current field and begin the next, the current field is marked "finished" with a **red cursor**. The cursor will not return to this field again without positioning the cursor using the mouse.

Lists in Dialogue Boxes

There are two types of lists that occur in dialogue boxes: exclusive (choose one) and non-exclusive (many items can be chosen). Exclusive lists have entries that begin with a **red ">"** character. Non-exclusive lists have entries that begin with a **red "o"**. An option title/description is in white above the list.

For example,



Any number of items can be chosen.

Only one item can be chosen.

Choose an item of a list by pressing the left mouse button anywhere on the text of that entry. The text of the chosen entry will be **highlighted in yellow**. **To deselect the entry, press the left mouse button on the entry again**.

When an entry of an exclusive list is chosen, the other entries disappear from sight. The hidden entries reappear if the selected entry is deselected.

Executing a Dialogue Box

Press the **EXEC**ute button at the bottom of the dialogue box to issue the command. Any number of error conditions will prevent execution of the dialogue:

(a) Not all input fields are filled in,
(b) Not all input fields have been flagged as "complete". Pressing ENTER causes the field to be checked for completeness. Complete fields have red cursors at the end.
(c) No entry has been chosen for a list that requires a choice to be made.
(d) **True*Grid*®** is in a state where a command is in progress.

If (a) or (b) occur, then the input field will be moved just below the top of the dialogue, and the prompt for the first offending field is colored blue. If (c) occurs, then the first entry of the offending list appears near the top of the dialogue, and the marker (either ">" or "**o**" is colored blue). If (d) occurs, the **EXEC**ute button is colored red.

To **EXEC**ute and **QUIT** the dialogue box, use the **EXEC/QUIT** button. This button is usually the best choice because it requires the least number of mouse actions.

Note: Pictures are not automatically redrawn when commands are issued in **True*Grid*®**. To insure that a new picture is drawn, press the **EXEC** button or the **EXEC/QUIT** button using the middle mouse button instead of the left mouse button. Doing so causes a draw command to be issued with the command.

Supported Geometry

Importing IGES Files

Internal Geometry Library

True*Grid*® can create a wide variety of surface types such as:

- sphere
- plane
- cylinder
- cone
- torus
- surface of revolution
- ruled surface
- swept surface (using skinning)
- extruded surface (general cylinders)
- surface interpolated between two other surfaces
- tabulated surface consisting of a 2D array of points
- surface composed of multi-sided polygons
- pipe surface from a 3D curve
- surface given by equations
- cubic spline surface
- B-spline surface
- NURBS surface
- Stereo Lithography surfaces
- compositions of any of the above

An extensive set of options for building 2D and 3D curves is also provided within **True*Grid*®**.

For more information, issue the `help` command for **ld** in the 2D CURVE sub-menu, **sd** is the SURFACE sub-menu, or **curd** in the 3D CURVE sub-menu.

Importing IGES Entities

True*Grid*® can extract most surface and curve entities from an IGES file. We presently support the following IGES Entities:

100 - Circular Arc
102 - Composite Curve
104 - Conic Arc
108 - Plane
110 - Line
112 - Parametric Spline Curve
114 - Parametric Spline Surface
118 - Ruled Surface
120 - Surface of Revolution
122 - Tabulated Cylinder
124 - Transformation Matrix
126 - NURBS Curve
128 - NURBS Surface
140 - Offset Surface
142 - Curve on a Parametric Spline Surface
144 - Trimmed Parametric Spline Surface
402 - Associativity Instance

Extracting All IGES Entities

All supported entities are extracted from an IGES file with the single command

```
iges IGES_file_name m n;
```

Issuing this command causes the specified IGES input file to be read and all curves and surfaces to be extracted. You can find this command in the CAD sub-menu. The surfaces are assigned **True*Grid*®** surface definition numbers beginning with *m*, and the curves are assigned **True*Grid*®** curve definition numbers beginning with *n* (where *m* and *n* are integers.) Note that curves used to construct others are not processed.

Selectively Extracting IGES Entities

Entities can be selectively extracted from an IGES file using a two-step process. First, specify the IGES file using the command (also in the CAD sub-menu)

```
igesfile IGES_file_name
```

Second, use either the `igescd, igessd,` or `nurbsd` command to extract curves, surfaces, or NURBS surfaces, respectively. These commands are all found in the CAD sub-menu, as well.

Example:

```
igesfile airplane.igs
nurbsd 1 24 1;
igessd 1 15 25;
igescd 1 87 2;
```

will cause **True*Grid*®** to

(a) read the IGES file 'airplane.igs';

(b) to extract the first 24 NURBS surfaces, and to create **True*Grid*®** surface definitions 1 to 24;

(c) to extract the first 15 surfaces (other than NURBS), and to create **True*Grid*®** surface definition numbers 25 to 40;

(d) to extract the first 87 curves from the IGES file, and to create **True*Grid*®** curve definition numbers 2 to 88.

Saving Time

Large IGES files may take some time to process within **True*Grid*®**. It can be time-consuming to tile all the surfaces for graphics purposes. Every time **True*Grid*®** is rerun and, consequently, asked to read the same IGES file, all this work must be repeated. To eliminate the need for subsequent processings of an IGES file, use the command

`saveiges` *`binary_output_file`*

Example: Suppose that after issuing the previous set of commands, the command

```
saveiges airplane.bin
```

is issued. Then the next time the same set of surfaces and curves are to be used, issue the commands

```
useiges airplane.bin
igesfile airplane.igs
nurbsd 1 24 1;
igessd 1 15 25;
igescd 1 87 2;
```

`The useiges command is also found in the CAD sub-menu.` **True*Grid*®** will process this set of commands many times faster than it was able to process the commands in the previous example.

Notes about `saveiges`

1. Only entities processed before the `saveiges` command are saved. (Entities are processed when either `igessd, igescd,` or `nurbsd` are issued.)

2. The name of the file used with the `saveiges` and the `useiges` commands must match *exactly*, or the binary IGES file will not be used.

3. The name of the file used with either the `igesfile` or `iges` command must be *exactly* the same as when `saveiges` was issued.

IGES Levels (Layers) and Groups

The layer or level feature commonly found in CAD systems can be used to organize the geometry for **True*Grid*®** use. The associativity instance is used for grouping the entities into levels. **True*Grid*®** preserves this level structure.

Interactive Graphics

Mouse Selection of Geometry

True*Grid*® Graphics

True*Grid*® provides dynamic control for rotating, translating, and zooming. Also provided is readily accessible control over what curves, surfaces, regions, etc. are in the picture and whether or not they are labeled.

Example: Run **True*Grid*®** using the command `tg` with no command-line options. There is no graphics capability in the Control Phase of the code, so issue the command

```
merge
```

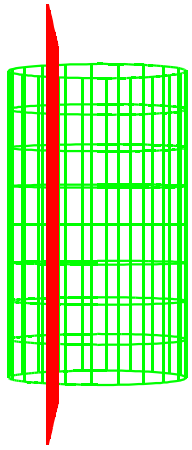
to enter the Merge Phase of the code.

Next create a couple of surfaces using the **S**urface **D**efinition command:

```
sd 1 cyli   0 0 0  0 1 0  2
sd 2 plan  -1 0 0  1 0 0
```

The first surface is a right circular cylinder of radius 2 whose axis of rotation passes through (0,0,0) and is parallel to (0,1,0). The second surface is a plane passing through (-1,0,0) and normal to (1,0,0).

The current picture in the Physical Window should appear similar to the one below



Even though the plane is actually perpendicular to the x-y plane, it appears somewhat slanted. This is because perspective is added to the picture, i.e., distant parts of the picture are smaller. The various circular cross sections of the cylinder differ from each other for the same reason. The perspective angle (the angle between the center of the picture and the edge of the screen) is controlled by the command

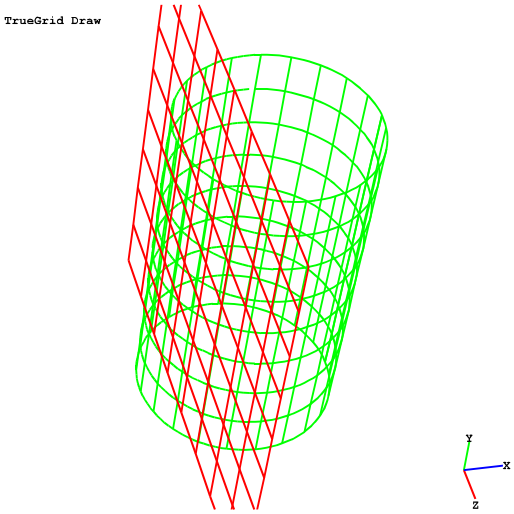
```
angle angle_of_perspective .
```

The default angle of perspective is 23 degrees. Setting the angle to 0 eliminates all effects of perspective.

Specifying the Type of Picture

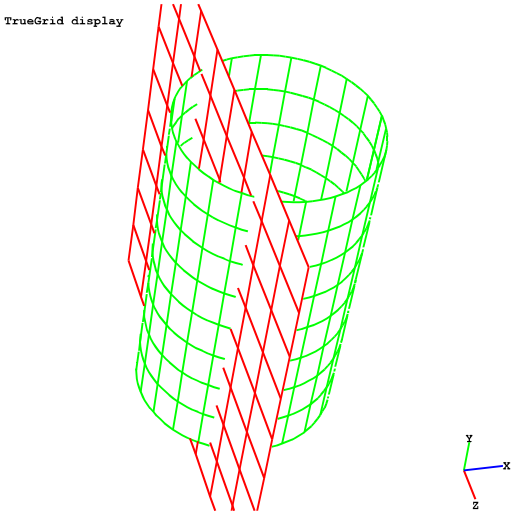
True*Grid*® can create several types of pictures. Which type of picture will be generated depends on the setting of the **Picture** button group in the **Environment** Window of **True*Grid*®** (shown above). The initial setting of the picture type is a **Hide** drawing (hidden lines are removed). The other types are described below. To choose a different picture type for all subsequently generated pictures, press the **left mouse button** on the desired picture type button (Wire, Hide or Fill). Changing the picture type does *not* cause a picture to be regenerated. A picture is redrawn by pressing either the **Draw**, **Cent**er or **Rest**ore button.

The simplest type of picture is a **Wire** frame drawing of all objects in the picture (the preceding picture is an example). Objects that would be hidden by others (in the real world) are not hidden in a **Wire** picture.



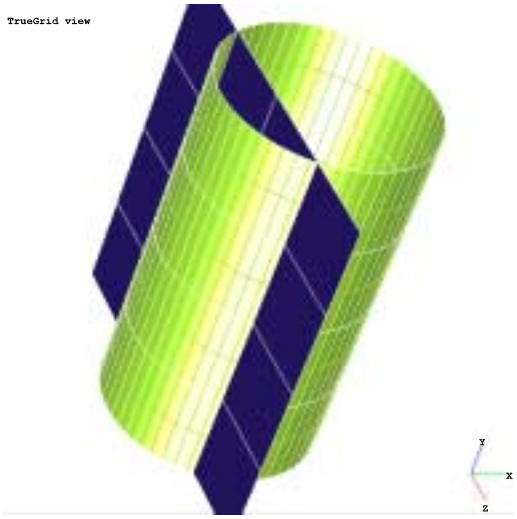
Picture Type: Wire

The **Hide** option is used for creating pictures whose hidden lines are removed.



Picture Type: Hide

The **Fill** option is used to create a picture where all polygons are filled and all hidden surfaces are removed. **For all but the PC Version, a two-source lighting model is used** (along with dithering to create a very smoothly lighted picture when only 8 bit plane graphics is available.)



Picture Type: Fill

When the picture type is set to **Fill**, several options concerning the lighting model can be changed via a **pop-up** menu which is accessed with the **right mouse button** in the **Physical Window** (not applicable to the PC version).

Hardware Graphics. We currently support hardware graphics features only for SGI versions of **True*Grid*®**. To invoke the graphics hardware features (lighting, fogging, material models, etc.), press the **H.W.** button using the left mouse. When hardware is invoked, the **Wire** option is the same as before, except that lighting and fogging models now apply. The **Hide** and **Fill** options no longer function differently; both set the picture type to a **Fill** type. Many parameters of the hardware model can be interactively changed using the **right mouse button** to activate a **pop-up** menu in the **Physical Window**.

Moving Around Interactively

The **Middle Mouse Button** is used to manipulate 3D graphics windows in **True*Grid*®**. The effect of pressing the middle mouse button in either the **Physical** or **Computational** window depends on which of the four buttons, **Rotate**, **Move**, **Zoom** or **Frame** is pressed. The buttons in this **Motion** button group of the **Environment Window** (pictured above) are reset by pressing the desired button using the left mouse button.

The Rotate, Move and Zoom options are all similar in nature. A dynamic operation is performed on the picture by moving the mouse to either the Physical or Computational Window, pressing the middle mouse button, and dragging the mouse to a new position while the middle mouse button remains pressed. As the mouse is moved, a minimal wire-frame representation of the picture is redrawn as quickly as possible. When the left mouse button is finally released, a new picture is redrawn. The type of the final picture is determined by the setting of the **Wire**, **Hide**, **Fill** button group.

Rotate. Horizontal movement of the mouse causes a rotation about a vertical line parallel to the screen plane. Vertical movement of the mouse causes a rotation about a horizontal line parallel to the screen plane. When the picture is magnified, rotations are reduced appropriately. This effect is eliminated by holding the "Shift" key down while rotating.

Move. The picture follows the mouse.

Zoom. Only vertical mouse movement causes a change. Move the mouse upward to enlarge the picture, and downward to shrink the picture. Moving the mouse half a window causes the picture to change by a factor of 10.

Frame. The Frame option is the fastest way to isolate some visible portion of the current picture. This is done by positioning a rubber-banded box around the part of the picture to be isolated; the framed part of the picture is then expanded to fill the entire graphics window. To frame part of the picture, first make sure the **Frame** button is pressed. Move the mouse into the graphics window and press the **middle mouse button** where you wish to place one corner of the framing box. Keep the middle mouse button pressed and drag the mouse to a new position. A rubber-banded square box will appear. Release the middle mouse button to view a wire frame, a hidden-line, or a polygon fill picture of the contents of the framing box (depending on the setting of the Wire, Hide, Fill buttons). To abort a frame operation in progress, drag the mouse outside of the graphics window and release the middle mouse button.

Drawing a New Picture

It is sometimes necessary to tell **True*Grid*®** to redraw the picture. This is especially true in the Part Phase, where commands are buffered – all buffered commands are executed whenever a new picture is generated. Also, if the user changes the type of picture to be drawn (Wire, Hide, Fill option), a new picture is not automatically redrawn; the user needs to tell **True*Grid*®** to redraw the picture.

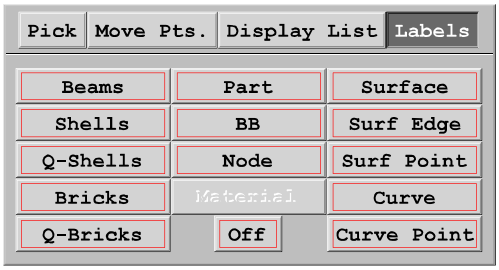
There are three basic ways to regenerate the picture. The first uses the **Draw** option. Invoking the **Draw** option (by pressing the **Draw** button with the **left mouse button**) causes the code to execute all buffered commands, and to generate a picture of the specified type (Wire, Hide or Fill) in the same position and orientation as the previous picture.

The **Cent**er option is used to adjust the picture so that all objects are fully visible within the window. The Center command leaves the rotational orientation of the picture the same as for the previous picture.

The **Rest**ore option also makes sure all objects are visible. However, the Restore command puts the picture back to the home (default) rotational orientation.

The Center and Rest commands are especially useful when objects are added or removed from the picture, or if the user gets lost in the picture.

Locating Objects Using Labels



Labels play an important role in interactive mesh generation. **True*Grid*®** allows the user to reference an object by pointing to its label. **True*Grid*®** never draws overlapping labels and, within this restriction, tries to center the label on the object. Furthermore, **True*Grid*®** highlights the object corresponding to a particular label when the user points to that label. (Assuming that the user has selected the "Labels" option under the "Pick" menu.) These features make it easy to find a particular object by its label, even when there are many objects in the picture.

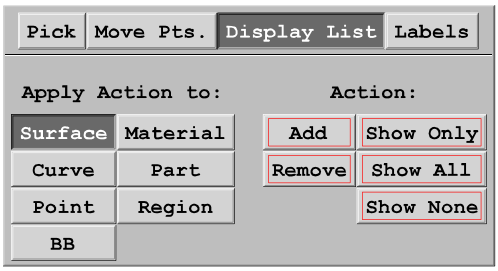
Only one class of objects is labeled at any given time. The user selects the class of objects to be labeled by first selecting the **Labels Dialogue** of the **Environment Window** by pressing the **Labels** button with the **left mouse button**. Then the user presses the button corresponding to the class of objects to be labeled. Pressing the **Off** button removes all labels.

Example. (Continuing with the current example.) Press the **Surface** button to display labels for the plane and cylinder in the picture. Move the mouse into the Physical Window and press the **left mouse button** on one of the two labels in the picture. Pointing in this fashion to label 1 highlights surface definition 1, which is the cylinder. Similarly, pointing to label 2 highlights the sphere. Pressing the left mouse button anywhere else in the picture clears the highlighting.

Next press the **Surf Point** button. Points on the plane (used mainly for graphical purposes) are now labeled. **True*Grid*®** allows the user to attach points of the mesh directly to such surface points. Zooming in on part of the picture will reveal more labels and points that can be used while building the mesh.

The **Surf Edge** button will label the edges of all defined surfaces in the picture. Edges of the mesh can be directly placed on such surface edges. When surfaces are infinite, as in the example, they have no useable edges; their edges can be displayed and highlighted but cannot be used in interactive meshing. This is because edges of infinite surfaces change, depending on the size of the bounding box for the picture.

Specifying What Objects Get Put in the Picture



The **Display List** dialogue of the **Environment Window** provides an interactive way to add and remove objects from the picture. Pressing the **Display List** button of the Environment Window activates this dialogue.

The group of buttons on the left is used to select the class of objects to which commands in this dialogue will apply. The group of buttons on the right execute commands to selectively add objects to or remove objects from the picture.

Removing an Object from the picture is done by highlighting the object (using the label highlighting feature described above), and then by pressing the **Remove** button with the left mouse button.

To Remove All Objects Except One, highlight the object to remain (using the label highlighting feature described above), and then press the **Show Only** button with the left mouse button.

Remove All Objects of the Specified Class by pressing the **Show None** button with the left mouse button. Removing all surfaces, for example, makes the mesh easier to view.

Add All Objects of the Specified Class to the picture by pressing the **Show All** button with the left mouse button.

The Add Feature also works on selected objects. Using the Computational Highlighting System for the mesh in the Part Phase, it is possible to select a region of the mesh that is not in the picture. Such a region is then added to the picture by pressing the **Add** button with the left mouse button. Notice that the **Region** button is grayed out in the Merge Phase because it is not possible to point to a region of the mesh in this phase of the code.

All of the interactive functions presented so far (except for the frame feature) correspond to commands that can be issued from the text and menu window of **True*Grid*®**. On the other hand, there are graphics commands that have no interactive counterparts. For example, there is no interactive command to add a surface, curve, etc. to the picture.

Presented below is a list of **True*Grid*®** commands that are analogous to the interactive functions presented so far.

Generate a New Picture

Generate a line drawing
`draw`
Generate a hidden-line drawing
`disp`
Generate a polygon fill drawing
`tvv`
Center the picture (do not change the rotational orientation)
`center`
Center the picture in the default orientation (with no rotations)
`rest` or `restore`

Rotate, Translate, Zoom

Rotate the picture about a horizontal line parallel to the screen plane
`rx` *angle_in_degrees*
Rotate the picture about a vertical line parallel to the screen plane
`ry` *angle_in_degrees*
Rotate the picture about a line perpendicular to the screen plane
`rz` *angle_in_degrees*
Zoom Forward by a factor (that can be less than 1)
`zf` *zoom_factor*
Zoom Backward by a factor (that can be greater than 1)
`zb` *inverse_zoom_factor*

Label Objects in the Picture

`labels` *option*
where *option* can be
`sd -` to label surfaces
`crv -` to label curves
`sdedge -` to label surface edges
`sdpt -` to label points on surfaces
`crvpt -` to label curves
`off -` to remove all labels

Specify the Surfaces Shown

Display **A**ll **S**urface **D**efinitions
`dasd`
Remove **A**ll **S**urface **D**efinitions
`rasd`
Display a single **S**urface **D**efinition
`dsd` *surface_definition_number*
Display a list of **S**urface **D**efinition**S**
`dsds` *list_of_surface_definitions* ;
Add a **S**urface **D**efinition
`asd` *surface_definition_number*
Remove a **S**urface **D**efinition
`rsd` *surface_definition_number*

Specify the Curves Shown

Display **A**ll **C**urve **D**efinitions
`dacd`
Remove **A**ll **C**urve **D**efinitions
`racd`
Display a single **C**urve **D**efinition
`dcd` *curve_definition_number*
Display a list of **C**urve **D**efinition**S**
`dcds` *list_of_curve_definition_numbers* ;
Add a **C**urve **D**efinition
`acd` *curve_definition_number*
Remove a **C**urve **D**efinition
`rcd` *curve_definition_number*

Specify the Parts Shown

Display **A**ll **P**arts
`dap`
Display one particular **P**art
`p` *part_number*
Add a **P**art to the picture
`ap` *part_number*
Remove a **P**art from the picture
`rp` *part_number*

Specify the Materials Shown

Display **A**ll **M**aterials
`dam`
Display a specific **M**aterial
`m` *material_number*

Add a **M**aterial to the picture
`am` *material_number*
Remove a **M**aterial from the picture
`rm` *material_number*

Specify the Regions Shown

These commands apply only in the Part Phase. The distinction between a Region specification and an Index Progression specification are explained later.

Display **A**ll **Reg**ions
`darg`
Display a specific **Reg**ion
`rg` *region*
Display a **Reg**ion specified by **I**ndex Progression
`rgi` *progression*
Add a **Reg**ion to the picture
`arg` *region*
Add a **Reg**ion specified by **I**ndex Progression
`argi` *progression*
Remove a **Reg**ion from the picture
`rrg` *region*
Remove a **Reg**ion specified by **I**ndex Progression
`rrgi` *region*

A Single Block Part

Making a Single Block Part

Introduced Here:

The Block Command
Projection Method
Intersection Algorithm
Computational
Highlighting System
Interpolation

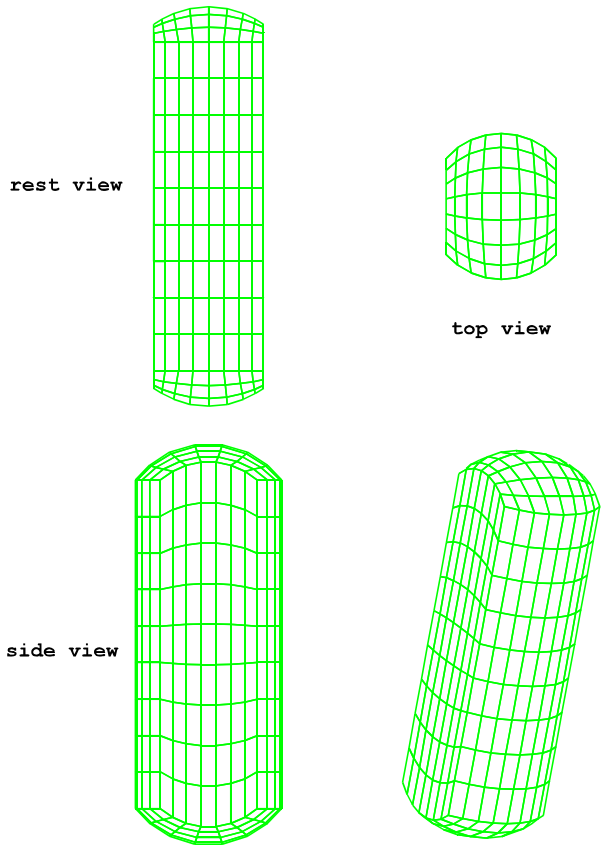
Prerequisites

The previous sections on interactive graphics, labeling objects, and choosing objects by label.

Description

A single block part is created. Each of the six faces in projected to a different surface to form a rounded-end rod.

True*Grid*® automatically places the edges of the block along intersections of the surfaces. The corners of the block are automatically placed at the intersections of three surfaces. The default interpolation takes care of the interior nodes.



Getting Started

Run **True*Grid***® with no input file. Enter the Merge Phase by typing the command

```
merge
```

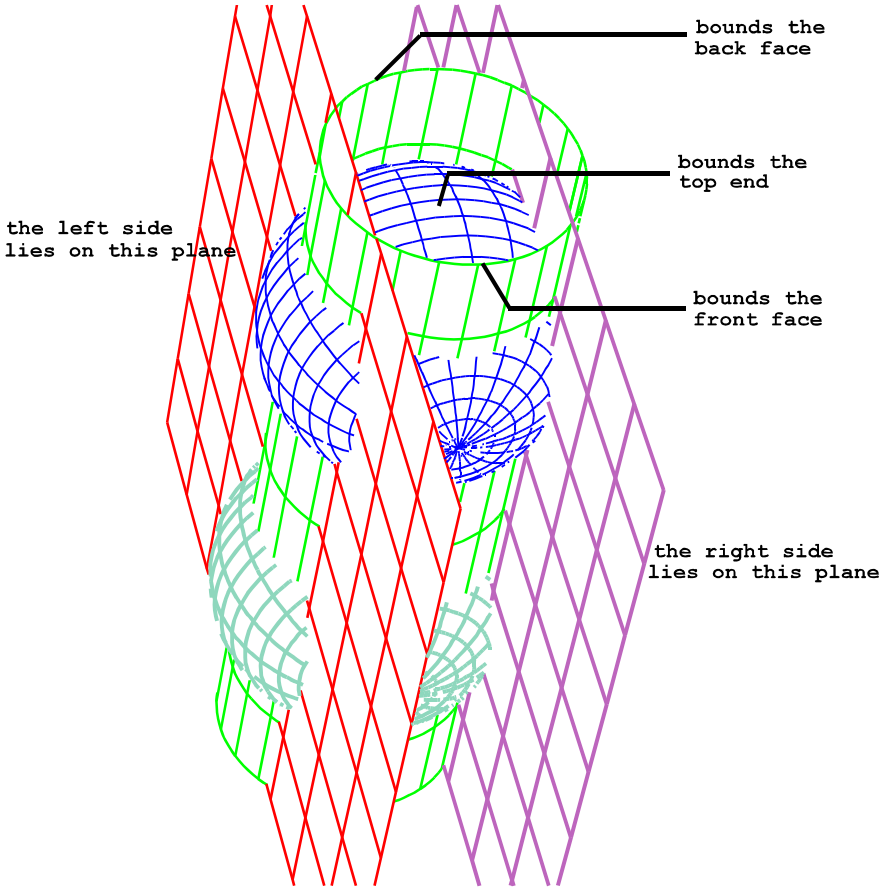
followed by a return. This allows you to view the geometry for this problem as it is being created.

The Geometry

The mesh is determined by just a few surfaces. The commands to create the geometry are listed below.

```
sd 1 cyli  0 0 0  0 1 0  2
sd 2 plan -1.5 0 0  1 0 0
sd 3 plan  1.5 0 0  1 0 0
sd 4 sphe  0 -3 0  2.5
sd 5 sphe  0  3 0  2.5
```

As an experiment, enter only part of a given command before pressing **ENTER**. **True*Grid***® will prompt you for the next required parameter of the command. You may enter as much of the command after the prompt as you wish (even part of the next command).



Pressing the **ESC**ape **KEY** in the middle of a command aborts that command. Another way to correct any mistake is to simply redefine the surface.

Surface Definition 1 is a right circular cylinder of radius 2 whose axis of rotation passes through (0,0,0) and is parallel to (0,1,0). Both the front and back faces of the rod will lie on this cylinder

Surface Definition 2 is a plane passing through the point (-1.5,0,0) and perpendicular to (1,0,0). The left face of the rod will lie on this plane.

Surface Definition 3 is a plane passing through the point (1.5,0,0) and perpendicular to (1,0,0). The right side of the rod will lie on this plane.

Surface Definition 4 is a sphere centered at (0,-3,0) and of radius 2.5. The bottom end of the rod will lie on this sphere.

Surface Definition 5 is a sphere centered at (0,3,0) and of radius 2.5. The top end of the rod will lie on this sphere.

The Block Command

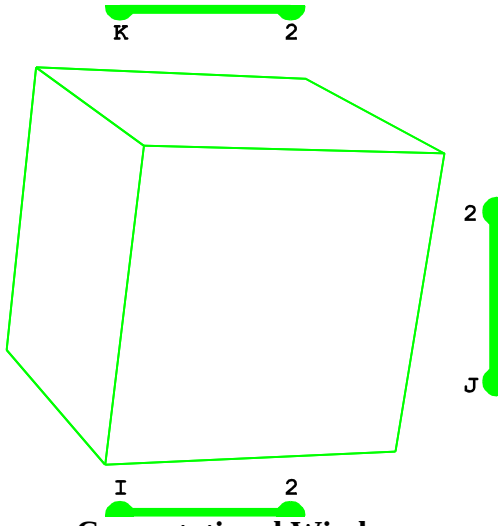
The actual mesh is now created using the `block` command. At the **`merge>`** prompt enter

```
block  1 9; 1 10; 1 8;
      -2 2;-6  6;-2 2;
```

(The command can be entered on one line or split across lines as shown.)

This block command creates a single block mesh with 9 nodes in the i-direction, 10 nodes in the j-direction, and 8 nodes in the k-direction. The x-coordinates of these nodes are evenly spaced between -2 and 2, the y-coordinates evenly spaced between -6 and 6, and the z-coordinates evenly spaced between -2 and 2.

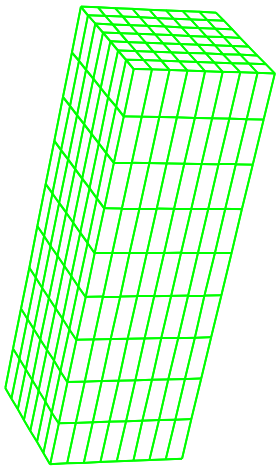
As soon as the block command is finished, **True*Grid*®** switches to the **Part Phase**. A new window with a title *Computational* appears in the upper right corner of the screen. The Computational and Physical pictures will not be drawn until the user tells **True*Grid*®** to draw these pictures.



Computational Window

The Computational Window contains a block representation of the mesh. Along the lower, upper, and right borders of the window are **index bars**. These index bars provide a means by which the user can select any corner, edge or face of the block, as well as the solid block. Such a selection can then be used directly in any command requiring a description of part of the mesh as one of its arguments.

The computational picture would not be so useful if all that could be created within **True*Grid*®** was a single-block mesh. However, **True*Grid*® allows the user to create a three-dimensional array of blocks using the block command**. In fact, all but the simplest meshes built with **True*Grid*®** will tend to be multiple-block meshes. And for multiple-block meshes, the **Computational Highlighting and Selection** system is a powerful tool for both mesh editing and setting boundary conditions.



Physical Window

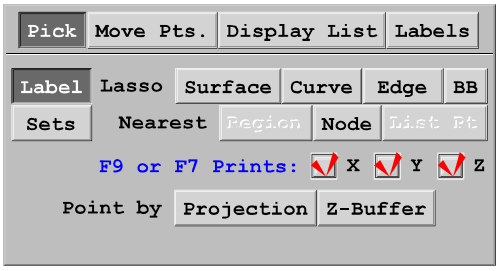
The Physical Window contains a picture of the actual mesh. To distinguish between geometry and mesh, mesh lines are green, surfaces are red, and curves are yellow. Of course, highlighting changes the color of the highlighted object. *The green mesh lines are not just a rough representation of the mesh. Any time the user redraws the physical window, all buffered commands are executed and the actual mesh is displayed.*

Setting the Window

Because there are two graphics windows in the Part Phase, it is necessary to inform **True*Grid*®** which window is to be acted upon. This is done by pressing the **left mouse button** on either the **Phys**ical, **Comp**utational or **Both** button.

When either the **Draw**, **Cent**er or **Rest**ore buttons is pressed, the appropriate window is redrawn. The same is true of manually issued commands such as **rx**, **ry**, **rz**, etc. The user should also be aware that commands such as those to reset the angle of perspective are also directed to the window indicated by the setting of **Phys**, **Both** and **Comp** button group.

Configure **True*Grid*®** to Choose Surfaces by Label



There are three different functions for the left mouse in the Part Phase Physical Window. The left mouse button can be used to **choose objects by their labels**, to **choose the nearest mesh vertex**, and to interactively **move portions of the mesh**. You must explicitly tell **True*Grid*®** which of these actions to perform. (There was no need to do this in the Merge Phase, because the left mouse button was used only to highlight a labeled object.)

Finishing the problem at hand requires a few interactive projections. An interactive projection requires the user to highlight a face of the mesh, and to highlight a surface. Therefore, for the purposes of projection, press the **Pick** button in the Environment Window to obtain the **Pick Dialogue** pictured above. Then press the **Label** button to inform **True*Grid*®** that you wish the left mouse button to be used to pick an object by its label.

Notice the sketch of the mouse with the left mouse button marked. All functions using the left mouse button in the Physical Window are clearly marked in this manner.

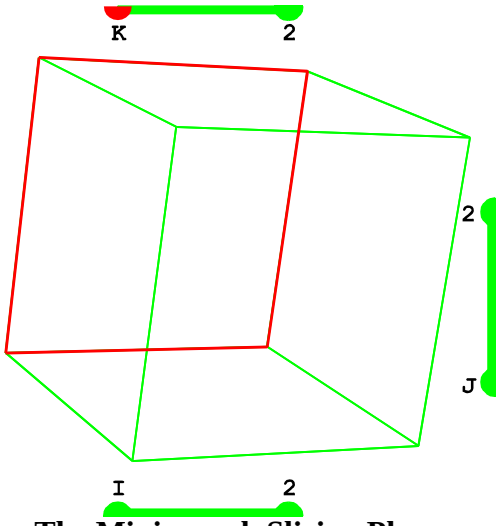
Now **True*Grid*®** is set up to pick a surface by its label. So highlight the cylinder by finding the appropriate label (this is surface definition 1).

Highlight Faces of the Mesh to be Projected

The front and back faces of the mesh are to be projected to the cylinder that was just highlighted. These faces can be simultaneously selected for just this purpose. **The Computational Highlighting System** of **True*Grid*®** is the general purpose tool for selecting and examining parts of the mesh.

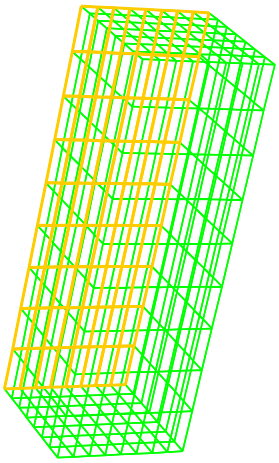
The first component of this unique highlighting system is a **Slicing Plane** (illustrated below). The slicing plane feature is activated whenever the mouse is moved into the Computational Window near one of the dots of the index bars. The dot near the mouse turns white, and a corresponding block

face in the Computational Window is highlighted in white.



The Minimum k Slicing Plane

The corresponding mesh face in the Physical Window is also highlighted in white.



Corresponding Physical Mesh Face

Notice that, in this example, when the mouse is near the left-most dot of the upper index bar, that the back face of mesh is highlighted.

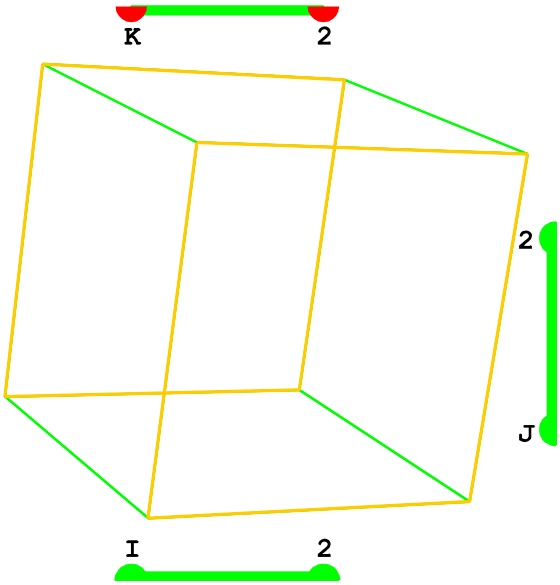
Dots on the lower index bar correspond to faces where the i-index is held constant; dots on the right index bar correspond to constant j-index faces; dots on the top index bar correspond to constant k-index faces. By convention, the actual values of fixed indices increase from left to right and bottom to top.

Now select the back face of the mesh by first highlighting that face (as shown above) and then by pressing the **left mouse button** while the minimum constant k slicing plane is active. The back face of the computational block and the back face of the mesh will both turn yellow.

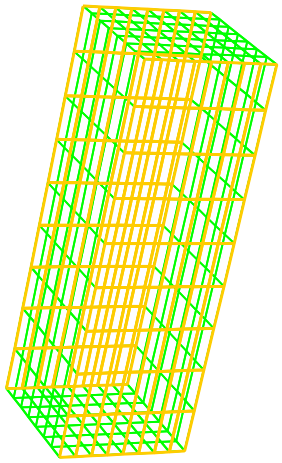
If you make a mistake while making the selection, press the **F2 KEY** to clear the selection (this will not clear any slicing plane).

Next move the mouse until the maximum k slicing plane is active (equivalently, when the right dot on the top index bar is white). The highlighted face of the mesh is the front face. Add this face to the current selection by pressing the left mouse button while the maximum k slicing plane is still active.

At this point, both the front and back faces of the mesh will be highlighted in yellow. The two dots of the upper index bar will be red. The cylindrical surface you highlighted earlier should still be highlighted. The final computational selection appears below.



Front and Back Faces Selected



Front and Back Mesh Faces

Now that the faces of the mesh to be projected and the surface to which they are to be projected are both highlighted, then the required projection can be performed.

Perform the projection of the highlighted mesh faces to the highlighted surface by pressing the Project button.

In case of a mistake, deactivate the projection command by pressing the **Undo** button in the **Edit** button group of the Environment Window.

Pressing the Undo button will undo the last active meshing command. So pressing the Undo button many times will undo many meshing commands. (The Undo feature does not apply to graphics commands.) There are more sophisticated ways to selectively deactivate meshing commands. Such techniques will be discussed later.

It should not be difficult to finish this problem. There are four other projection commands required. The minimum i-face should be projected to the plane on the left (surface definition 2). The maximum i-face should be projected to the plane on the right (surface definition 3). The minimum j-face (bottom) should be projected to the bottom sphere (surface definition 4). The maximum j-face (top) should be projected to the top sphere (surface definition 5). Keep in mind that the F2 KEY clears the computational selection, and that Undo will reverse the effects of any meshing command such as a projection.

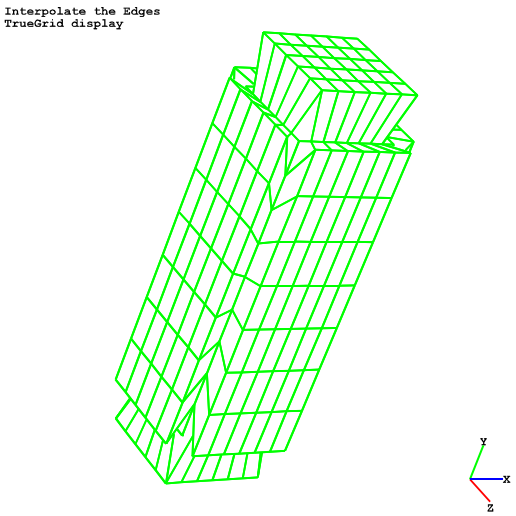
In the next sections, there is more about the activating and deactivating commands, more about the computational highlighting system, and information concerning how this single block mesh is handled internally. All of these sections reference this example.

More About the Part

How **True*Grid*®** Built the Mesh

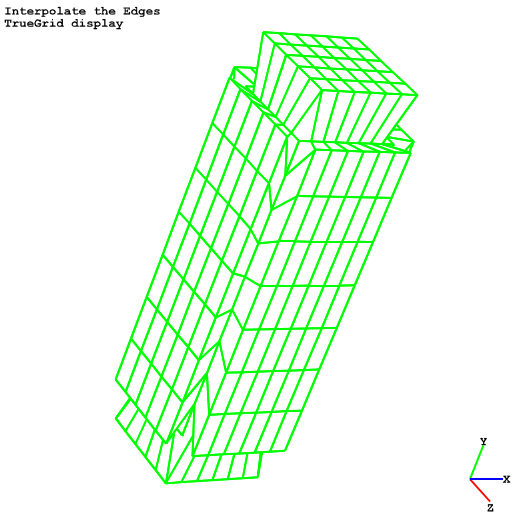
The previous example provides a wonderful illustration of the projection method of **True*Grid*®**. For this previous example, we describe the method used by **True*Grid*®** to build the single block mesh. Snapshots of the mesh in various unfinished states are used for illustration purposes. You never actually see the intermediate pictures.

Step 1: True*Grid*® begins with the corners of the block (or blocks, for a multiple-block mesh). In the case at hand, each corner of the mesh is required to be on 3 different surfaces. So **True*Grid*®** first places each corner at the intersection of the 3 surfaces on which the corner is to lie.



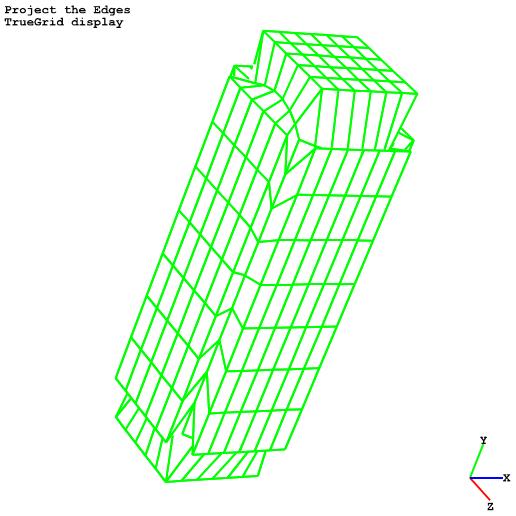
Step 1: The Corners are Positioned

Step 2: After the corners of a block are positioned, the edges are interpolated using the default interpolation method of **True*Grid*®**. For edges this amounts to pulling the edges tight as though they were strings, and then evenly spacing the nodes along the edges.



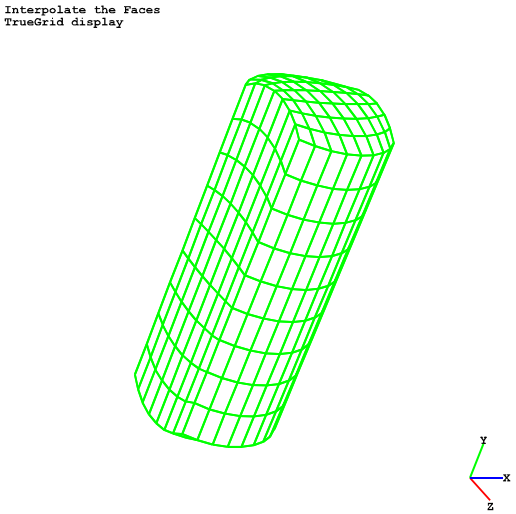
Step 2: Interpolate Edges

Step 3: The edges of the blocks are now projected to the surfaces on which they must lie. In this example, all edges are required to be on two different surfaces. So **True*Grid*®** places all the interior nodes of a given edge onto the intersection of the two surfaces on which these interior edge nodes are to lie. Then **True*Grid*®** equally spaces these nodes along this intersection curve (because there are no clustering requirements in this case).



Step 3: Edges are Projected

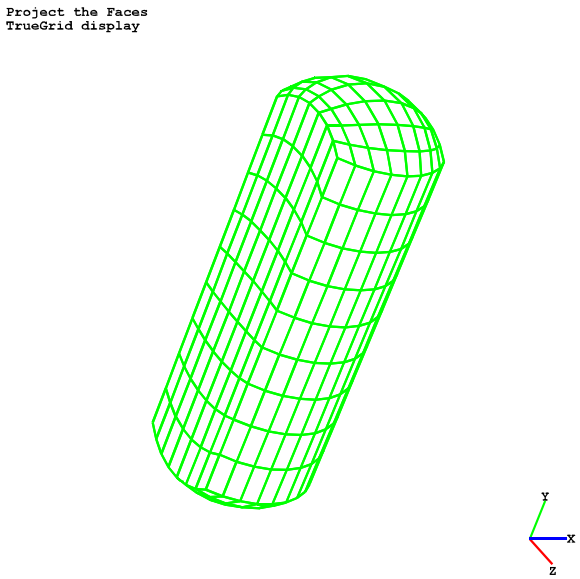
Step 4: Using the edges, all faces of the mesh are now interpolated. Many faces end up (by accident) in their final positions. For example, the faces that must lie on planes have edges that already lie on planes and, consequently, the interpolated faces end up on planes. However, the top and bottom ends of the rod are not correctly positioned. The top and bottom ends are required to be on spheres.



Step 4: Interpolate Block Faces

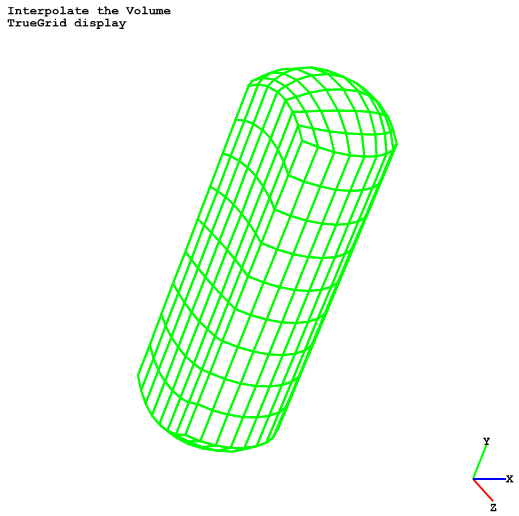
Step 5: The interior nodes of faces of the mesh are now projected onto the surfaces on which they are required to lie. Nearly all nodes were already correctly positioned (by accident). Only the top and bottom ends of the rod, which must lie on spheres, end up being repositioned.

At this point the mesh appears to be finished. However, there is no telling where the interior nodes may be at this point. Because the interior nodes of the block (not pictured) have never been touched, it is even possible that some of these nodes now lie outside the volume of the actual problem.



Step 5: Block Faces are Projected

Step 6: As a final step, the interior nodes of the block are interpolated using the positions of the nodes on the block faces. The mesh is complete.



Step 6: Interpolate Interior Block Nodes

There is no difference between the last picture and the previous because interior nodes are not shown in either.

The History Table: Turning Commands Off and On

A **History Table** of commands is kept by **True*Grid***®. All the commands in the history table can be viewed by pressing the **History** button in the **Edit** button group of the Environment Window.

The history is also summoned by entering the

```
history
```

command at the text window prompt.

The history appears in the text/menu window. The entire history table will probably not be visible at one time. There are several solutions to this problem. Put the mouse in the text/menu window and using the **up arrow**, **down arrow**, **page up** or **page down** keys to scroll the text. Alternatively, use the **scroll bar** on the right side of the window. Another solution is to enlarge the window.

For the present example, the history table contains all the projection commands. (The order of the commands in the table depends on the order in which they were issued.)

```
 H I S T O R Y   T A B L E

active 2 surface projection
 progression 1 2; 1 2; -1 0 -2;
active 3 surface projection
 progression -1 1; 1 2; 1 2;
active 4 surface projection
 progression -2 2; 1 2; 1 2;
active 5 surface projection
 progression 1 2; -2 2; 1 2;
active 6 surface projection
 progression 1 2; -1 1; 1 2;
```

Each entry of the history is composed of two lines. The first line of each entry begins with one of three words indicating the status of the command: **active**, **deactivated**, or **inactive**. Immediately following the status is a **command sequence number**. Command sequence numbers are assigned sequentially when the command is issued. The last part of the first line contains a **brief description of the command**. The next line begins either with **region** or **progression**, indicating which of the two ways of specifying part of the mesh was used.

Highlighting the Part of the Mesh to which a Command Applies

Press the **middle mouse button** anywhere on the second line of the history entry for a command to highlight the part of the mesh to which a command applies. (This line begins with either "progression" or "region".) Notice that both the computational and physical windows are highlighted. This highlighted region can be used in subsequent commands, or modified and used in subsequent commands.

Deactivating and Reactivating Commands

To deactivate a command whose status is "active", press the **middle mouse button** on the word "active". A command is generated on the command line which, when issued, will deactivate the given command. Press return to issue this command. Multiple commands can be issued at one time. Redraw the picture to see the result.

To reactivate a command whose status is "deactivated", press the **middle mouse button** on the word "deactivated". A command is generated on the command which, when issued, will reactivate the given command. Press return to issue this command. Multiple commands can be issued at one time. Redraw the picture to see the result.

Example. Use the history highlighting feature to isolate the command requiring the

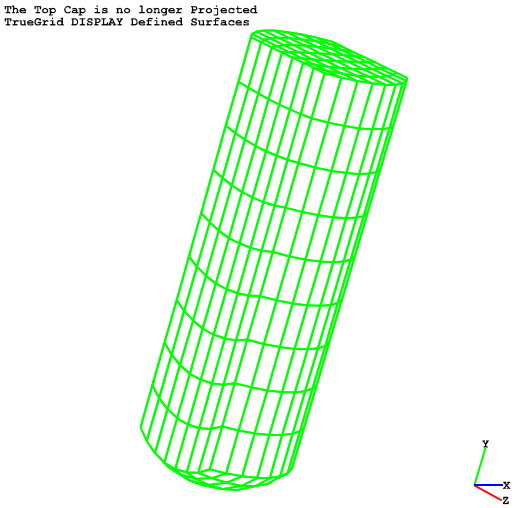
top end of the rod to be projected. The progression line of that command appears as

```
progression 1 2;-2 2;1 2;
```

On the line just above the progression description, press the middle mouse button on the word "active". A command such as

```
decmd 5
```

appears on the command line of the text/menu window. Press ENTER to issue this command. A picture is not automatically regenerated, so press the Draw button in the environment window.



The Top End is not Projected to the Sphere Anymore

Notice that the top end of the bar is no longer projected to the sphere. Press the History button again to see the new history table.

```
 H I S T O R Y   T A B L E

active 2 surface projection
 progression 1 2; 1 2; -1 0 -2;
active 3 surface projection
 progression -1 1; 1 2; 1 2;
active 4 surface projection
 progression -2 2; 1 2; 1 2;
deactivated    5    surface
projection
 progression 1 2; -2 2; 1 2;
active 6 surface projection
 progression 1 2; -1 1; 1 2;
```

Notice that the history table reports the status of the command you selected to be "deactivated".

Reactivate the command by pressing the middle mouse button on the word "deactivated", and by pressing ENTER. Again, draw the picture to see that the top end of the rod is back on the sphere. Pressing the History button will print a history table that reports the command status to be active.

Inactive commands cannot be deactivated. Such commands only occur when using certain very advanced features of **True*Grid*®**. No such examples occur in this tutorial.

Interactively Changing the Mesh Density

Modify **SEQ**uence (**mseq)**

The `mseq` command is used to change the mesh density. For example, the block command

```
block 1 9; 1 10; 1 8;
     -2 2;-6  6;-2 2;
```

creates the same mesh as these commands

```
block 1 2; 1 2; 1 2;
     -2 2;-6 6;-2 2;
mseq i 7
mseq j 8
mseq k 6
```

The first mseq command adds 7 nodes in the i-direction. The next mseq command adds 8 nodes in the j-direction. The last mseq command adds 6 nodes in the k-direction.

The mseq command can also be used to remove nodes in one direction by using a negative number.

Refining the Mesh of the Previous Example. Just to illustrate how easy it is to refine the mesh without having to change any other commands, try the command

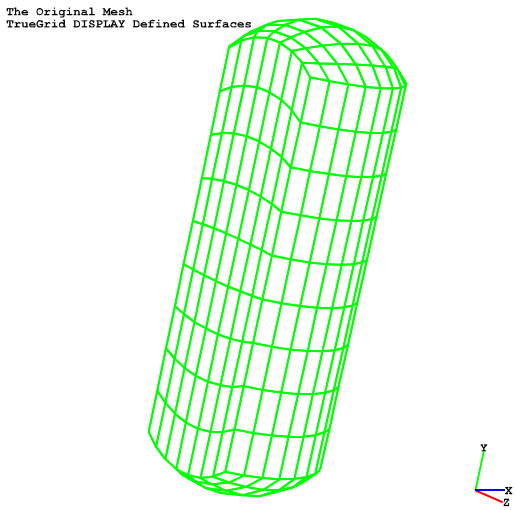
```
mseq j 10
```

To view the change, regenerate the picture by pressing the draw button.

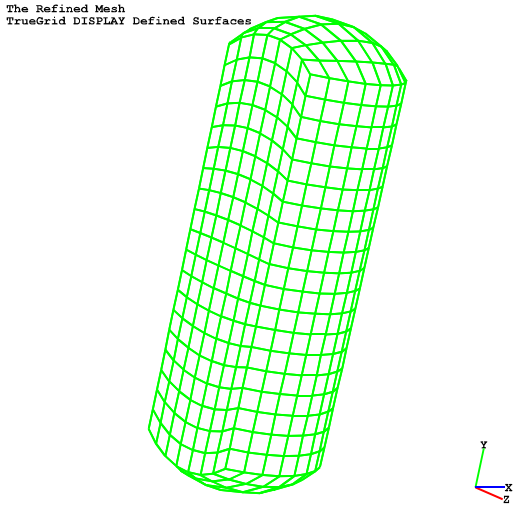
The effects of this command are reversed by the command

```
mseq j -10
```

As before, press the Draw button to view the changes to the mesh.



The Original Mesh



After the MSEQ Command

Clustering of Nodes (Zoning)

Relative **S**pacing Command (**res**)

SYNTAX:

`res` ***i_min j_min k_min i_max j_max k_max direction ratio***

where

direction can be either `i, j,` or `k, and`
ratio is a positive floating point number.

DESCRIPTION:

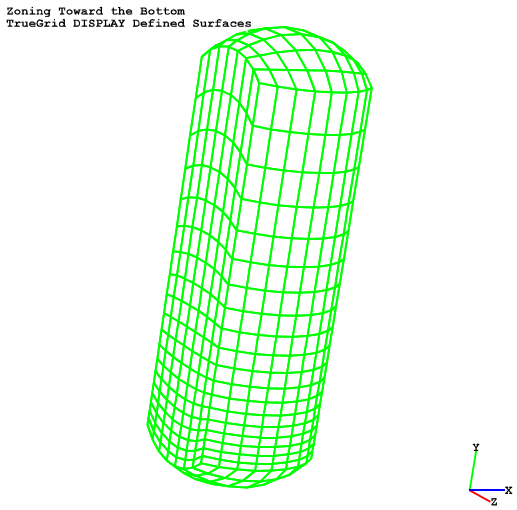
The nodes of all block edges of a specified region of the mesh are clustered in the specified direction. The amount of clustering depends on the ratio. The nodes are spaced so that the ratio of distances between adjacent nodes in the specified ***direction*** equals the given ***ratio***.

Thus, **for example**, if re-spacing is specified in the `i` direction with a ratio of `1.2`, then the nodes with smaller i-index values are closer together than those with larger i-index value. In particular, for a fixed j and k index, the distance between the nodes with i-index 2 and 3 will be 1.2 times as large as the distance between nodes with i-index 1 and 2. So in this case, nodes "cluster" in the negative i-direction.

Example. To cluster the nodes of the bar toward the bottom end of the bar, issue the command

```
res  1 1 1 2 2 2  j  1.1
```

To avoid typing the region description, first clear the computational highlighting by pressing the **F2 KEY**. Then type `res` on the command line, and press the **F1 KEY**. A description of the highlighted region is put onto the command-line following `res`. Because a null selection makes no sense in a command, **True*Grid***® converts the null selection to a description of the *entire mesh*. Finish the command by entering `j 1.1`.



Zoning in the j-direction

Clustering of Nodes (Zoning) in both Directions

Double **R**elative **S**pacing Command (**drs**)

SYNTAX:

`res` ***i_min j_min k_min i_max j_max k_max direction ratio1 ratio2***

where

direction can be either `i, j,` or `k`
ratio1 is a positive floating point number
ratio2 is a positive floating point number

DESCRIPTION:

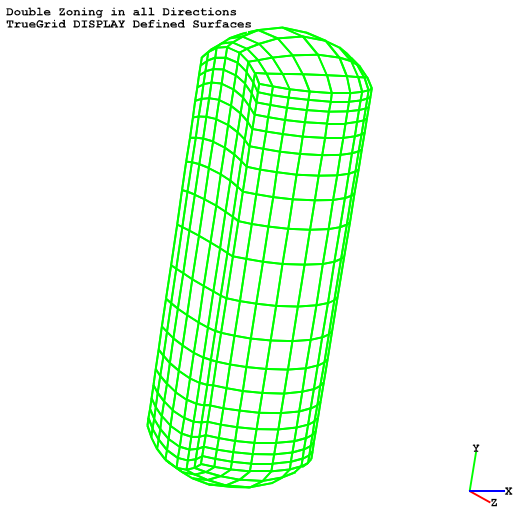
The nodes of the specified region are clustered in a given direction. Zoning near the minimum index of the given direction is controlled by the first ratio. Zoning near the maximum index of the given direction is controlled by the second ratio. If the second ratio is the reciprocal of the first, then `drs` works the same way as `res`.

Example. The `drs` command is particularly useful for fluids problems where nodes need to be clustered toward the walls of a mesh in order to resolve the boundary layer. To achieve such clustering for the current example, issue the three commands

```
drs 1 1 1 2 2 2  i  1.2 1.2
drs 1 1 1 2 2 2  j  1.2 1.2
drs 1 1 1 2 2 2  k  1.2 1.2
```

To avoid typing the region each time, use the same procedure described in the example of the `res` command.

NOTE: If you have already issued the `res` command of the previous example, there is no need to deactivate that command. Zoning commands for a region override previously issued zoning commands for that region.



Double Zoning in all 3 Directions

Saving and Rerunning the Session File

A **True*Grid*®** session file is written every time that **True*Grid*®** is run. If no session file name is specified on the command line (using the `s=` option), then the session file is named **tsave** and is placed in the current working directory. If the session file is named **tsave**, then make sure to rename the session file when finished, or it will be over-written the next time **True*Grid*®** is run.

Rerunning the Session File

A session file can be rerun as an input file (using the `i=` option). Running the session file as an input file is a good way to pick up where you left off the last time **True*Grid*®** was run. To run the session file as an input file, first remove the final command used to exit **True*Grid*®** (which can be `end, exit, adios, quit`). Otherwise **True*Grid*®** will exit without pausing for an interactive session. (There are times when you may wish to rerun the session file without any interactive session. In this case, leaving an exit command in the file is appropriate.)

When **True*Grid*®** is finished processing the input file, the user interface becomes active. A prompt appears in the text/menu window to indicate this fact. **True*Grid*®** will not automatically draw a picture unless a draw command has been placed in the input file.

The new session file will contain the lines from the original input file as well as any commands issued interactively after processing the input file.

Mixing Batch and Interactive Processing

True*Grid*® allows you to interrupt an input file at any point (even in the middle of a command) by placing

```
interrupt
```

in the input file. When **True*Grid*®** reaches the interrupt command, the user interface becomes active. A prompt appears in the text/menu window (upper left corner) to signal this fact. To process all the input file commands up to the next interrupt (or to the end of input file, whichever comes first), issue the command

```
resume
```

Alternatively, if **True*Grid*®** is stopped in either the Part or Merge Phase, then the **Resume** button in the Environment Window can be used (the Environment Window does not exist in the Control Phase).

When **True*Grid*®** reaches another interrupt command or the end of the input file, another interactive session begins.

The new session file produced will contain all the interactive and input file commands, in the order in which they were issued. The interrupt commands will be removed.

The Session and Input File Format

The session file is an ASCII file that is easily edited. **Only the first 80 characters of a line are considered by True*Grid*®**. Within a session file it is permissible to

1. Use upper or lower case letters,
2. Insert a comment anywhere,
3. Use any format for numbers,
4. Insert extra spaces anywhere,
5. Break a command across lines,
6. Insert graphics commands, or
7. Insert interrupt commands.

Comments are placed in the input file by placing a single `c` (or `C`) either at the beginning of the line or sandwiched between at least one space. All characters after the `c` and on the same line are treated as part of the comment. A comment may be inserted in the middle of a command. For example, **True*Grid*®** has no problem processing

```
c Create the Block Part
     block
  c Determine the Node
  c Distribution
        1  9;  c i-list
        1 10;  c j-list
        1  8;  c k-list
  c Specify the Coordinates
       -2  2;  c x-coordinates
       -6 -6;  c y-coordinates
       -2  2;  c z-coordinates
```

True*Grid*® uses a flexible format for numbers as well. For example, if **True*Grid*®** is looking for a floating point number, then any of the following will work (and will be treated equivalently):

```
1.0
.10E+01
.10e1
10.0E-01
1
```

If **True*Grid*®** is looking for an integer, any of the above will be interpreted as 1.

True*Grid*® also understands **FORTRAN expressions**, so long as they are enclosed by square brackets. All **FORTRAN** intrinsic functions are supported, including trigonometric functions and their inverses. All angles are assumed to be in degrees. For example, these are valid floating point numbers:

```
[tan(atan2(2,1))*3]
[(-2)*(-3)*4*5/4+3]
[sqrt(2)*sqrt(2)]
[2.3**2.5]
```

Parameters are defined using the `para` command and are referenced by preceding the parameter name with a `%` sign. The syntax for the `para` command calls for pairs of items (parameter name followed by a value) followed by a terminating `;`. For example, after the command

```
para x1 10
     x2 12
     x3 24;
```

then

```
[sqrt(%x1*%x2+%x3)]
```

is a valid expression whose value is 12. Note that parameters can be used as soon as they are defined. In particular,

```
para  x1 10  x2 [2*%x1];
```

results in a value of 20 for the parameter named x2. A single parameter can be referenced without brackets. For example, **True*Grid*®** understand `%x1` by itself, but it does not understand `-%x1`. `[-%x1]` is, however, understood by **True*Grid*®**.

Sphere in a Box:
A Multiple-Block Mesh

A Multiple-Block Part

Introduced Here:

Multiple Block Parts
Diagnostics
Deleting Blocks
Graphical Peeling

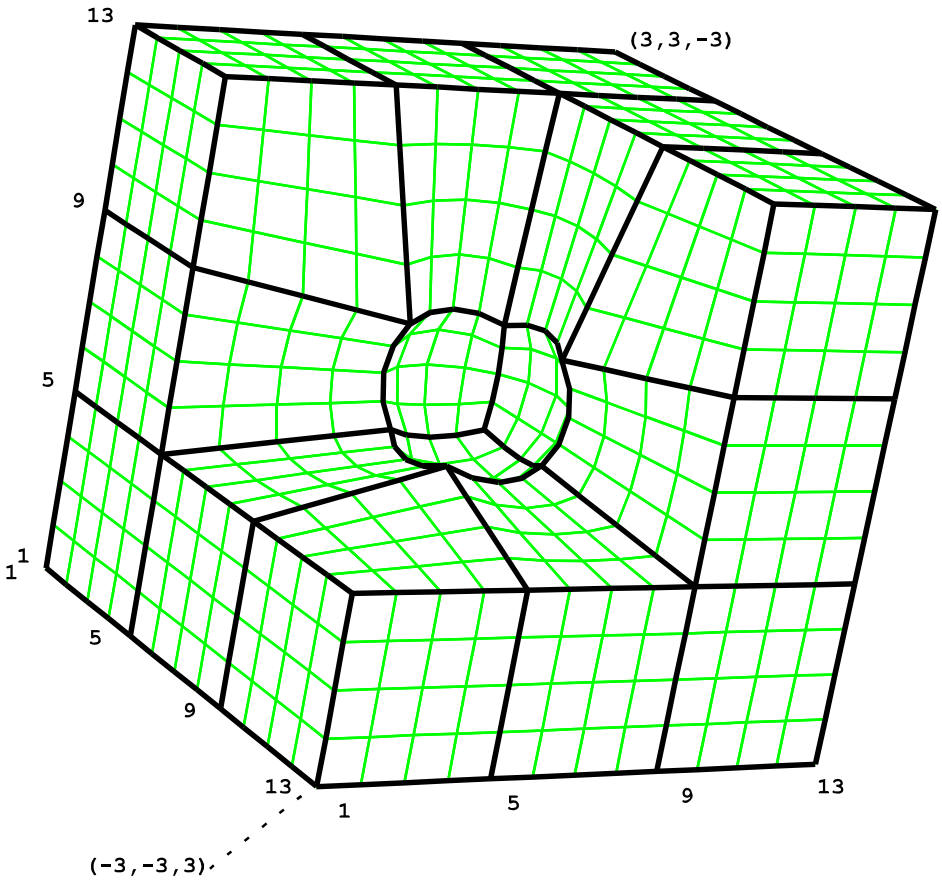
Prerequisites

Familiarity with graphics, labeling objects, and choosing objects by label. The single block example.

Description

A multiple-block mesh is constructed of the space inside a box and outside a sphere contained within the box. **This mesh is created with just four commands** that:

1. Create the multiple-block part,
2. Define the Sphere,
3. Make a hole in the mesh where the spherical cavity will be, and
4. Project the faces of the hole onto the sphere.



Cut-A-Way View of the Final 27-Block Mesh

Creating the Part

Run **True*Grid*®** with no input file. Instead of entering the Merge Phase as before, this time enter the `block` command straightaway.

```
block
  1  5 9 13;1 5 9 13; 1 5 9 13;
 -3 -1 1 3;-3 -1 1 3;-3 -1 1 3;
```

This command creates a 27-block part. The block boundaries are shown above.

What the Block Command is Doing

The syntax of the block command is

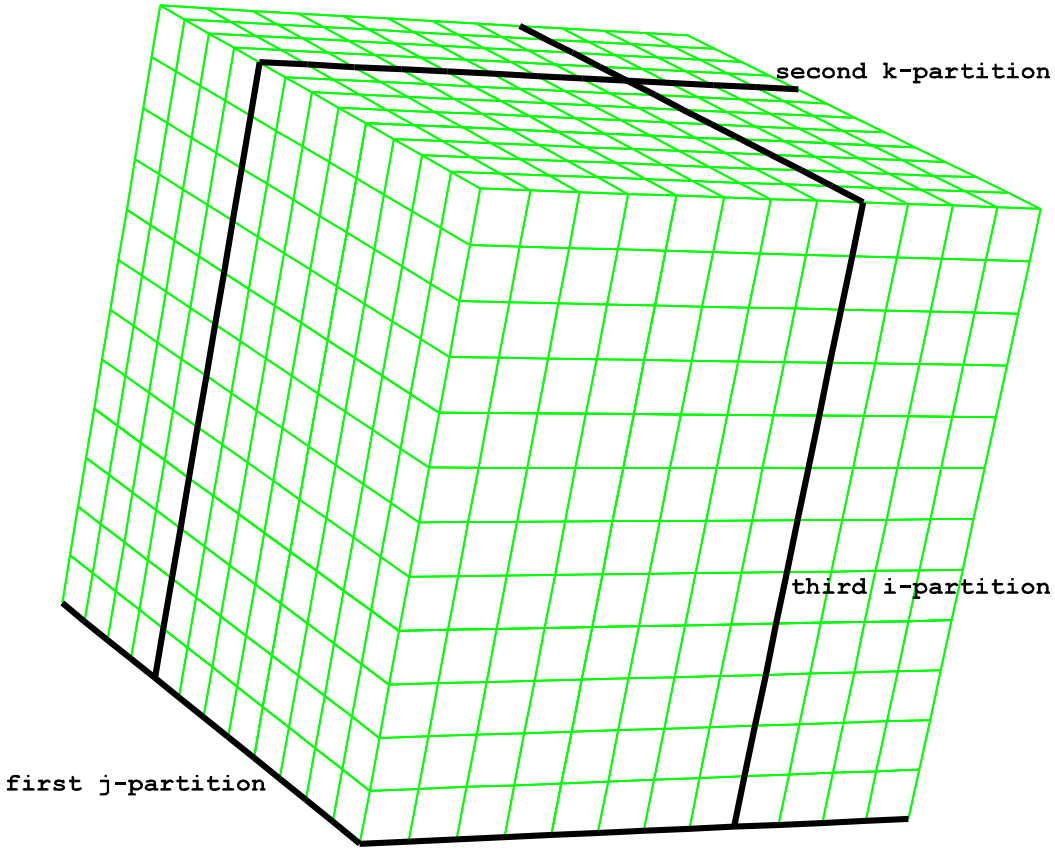
`block` ***i-list*** `;` ***j-list*** `;` ***k-list*** `;`
x-list `;` ***y-list*** `;` ***z-list*** `;`

The i-list, j-list and k-list must be terminated by a semicolon (;).

In this case, ***i-list*** consists of the numbers 1, 5, 9, 13, and ***x-list*** consists of the numbers -3, -1, 1, 3. If intermediate numbers are used in the ***i-list*** (5 and 9 are intermediate in this case), then **True*Grid*®** will subdivide the mesh in the i-direction at each place where the i-index is equal to one of these intermediate numbers. The corresponding intermediate values in the ***x-list*** are used to set the x-coordinates of the nodes at the subdivisions. An analogous statement applies to the j- and k-directions.

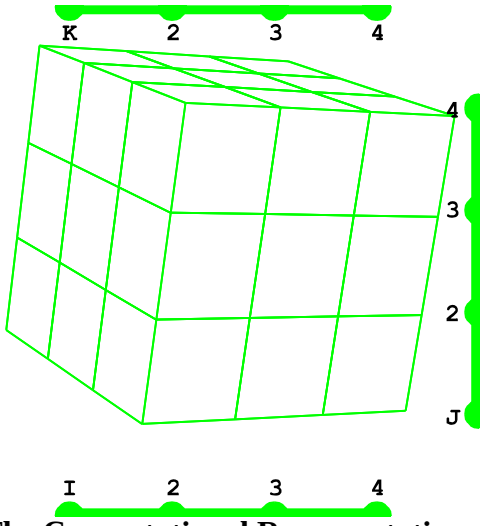
True*Grid*® Terminology: If ***n*** is a number in the ***i-list***, then the face where the i-index is held constant at ***n*** is called an **i-partition**. Similarly, a **j-partition** is a face where the j-index is held constant and equal to a number in the ***j-list*** of the block command. And, a **k-partition** is a face where the k-index is held constant and equal to a number in the ***k-list***.

Note: The mesh partitions shown below can be highlighted using the slicing plane feature.



Sample Mesh Partitions Created by the Block Command

The Computational Window always contains just the partitions created using the `block` command. The computational partitions are always shown a fixed distanced from each other and, therefore, each block in the computational picture is always a cube. For the current example, the computational picture contains 27 cubes (the user must issue a draw command to see the initial computational and/or physical pictures).



The Computational Representation

For the previous single-block example, no intermediate numbers were specified in either the ***i-list***, ***j-list*** or ***k-list*** of the `block` command. Therefore, there were just two partitions in each direction, leading to a computational representation which was a single cube.

The Consequences of Having Partitions

Each of the 27 blocks of the current mesh are treated as though they were single block meshes.

In particular, it is not possible to delete only part of a block. It is not possible to project only part of a block face onto a surface. It is not possible to zone just part of a block edge.

Furthermore, the same interpolation used to position the nodes within a single-block mesh is used here: The coordinates of corner nodes of blocks are used to interpolate edge node coordinates. Edge node positions are then used to interpolate face nodes. Face node positions are used to interpolate interior nodes. So, even though only corner node coordinates of the 27 blocks were specified using the `block` command, all nodes of the mesh have coordinates assigned to them.

Because of the way that individual blocks are treated, any unaltered mesh created using the `block` command will always consist of rectangular boxes whose nodes are equally spaced in the i-direction, equally spaced in the j-direction, and equally spaced in the k-direction. However, globally this need not be true because adjacent blocks do not necessarily contain the same number of nodes. All that can be said in general is that all blocks between two adjacent i-partitions have the same number of nodes in the i-direction, etc.

Finishing the Mesh

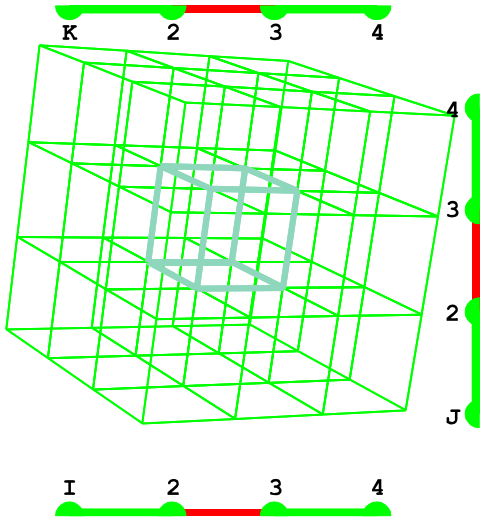
First **create a sphere** of radius 1 centered at the origin using the **S**urface **Definition** command

```
sd 1 sphe  0 0 0  1
```

This sphere will not be visible using the Hide option because the sphere is fully contained within the physical mesh.

Second, **delete the center block** of the 27-block part. This is easy to do using the Computational Highlighting System.

To do this, first highlight the solid center block as follows: Move the mouse into the computational window close to the second dot on the i-index bar (bottom window border). Press the left mouse button and drag the mouse to the third dot on the i-index bar. As you do this, the middle segment of the i-index bar turns red, and all blocks between the second and third i-partitions are highlighted in cyan. Release the left mouse button. Do the same in the j-direction using the j-index bar (right border of the window). This time only the blocks between the second and third i-partitions **and** those between the second and third j-partitions are highlighted in cyan. Do the same in the k-direction. Now only the middle block is highlighted (use the Wire option to see inside). **Note: Pressing the F2 KEY clears all highlighting.**



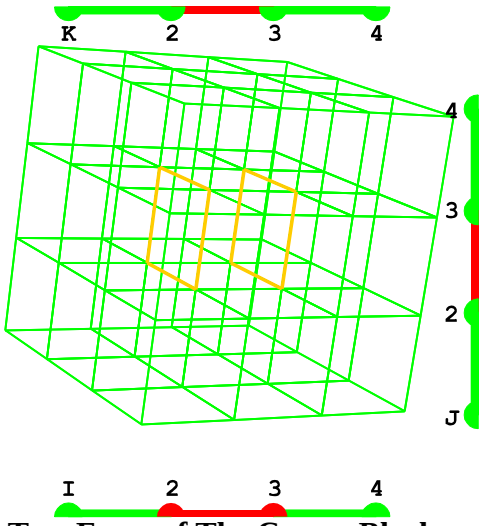
Highlight The Center Block

Next, press the **Delete** button in the **Edit** button group of the **Environment Window**.

Recall that meshing commands can be deactivated using the History feature. Alternatively, use the Undo button to deactivate the last active command.

Notice that after the new pictures are drawn, the highlighting of the center block has changed from cyan to magenta. This is a feature of the computational highlighting system: When part of a highlighted solid region is deleted, then faces of the deleted region contained within the solid are colored magenta.

Another unique feature of the computational highlighting system: **any combination of the 6 faces of a highlighted block can be selected at once**. As soon as one dot on a highlighted segment is activated, then the highlighting switches from solid to faces. Faces are highlighted in yellow as opposed to cyan for solids.



Two Faces of The Center Block

Notice the two activated dots on the i-index bar in the above picture. Activating these dots highlights the two corresponding i-faces of the center block. Similarly, any or all of the remaining 4 faces of the center block can be added to the current selection.

We want to project all six faces of the center block onto the sphere. So highlight all six faces by activating all six endpoints of the activated segments.

Now everything is set up to project. Instead of using a label to reference the sphere, try the command-line approach instead. First enter

```
sfi
```


on the command-line (in the text/menu window). Then press the **F1 KEY** to translate the highlighted selection into a numerical description of the selection. The numerical description will be appended to the current command line to give

```
sfi -2 -3;-2 -3;-2 -3;
```

The 2's and 3's indicate the partition numbers (second and third partitions in each direction). The negative signs indicate that the dots at 2 and 3 in all directions were turned on. If the segments connecting the dots had not be activated, then a 0 would have been inserted between the -2's and -3's.

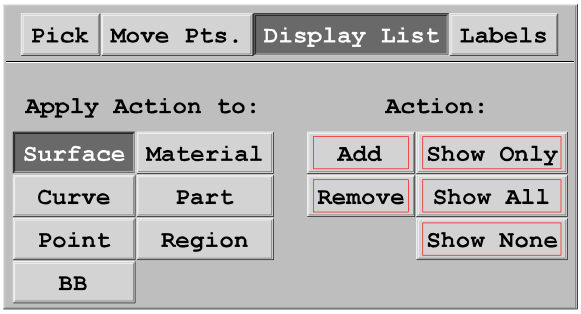
Finish the command by adding `sd 1` to the command-line and by pressing the **ENTER** key. The final command is

```
sfi -2 -3;-2 -3;-2 -3; sd 1
```

You must issue a draw command to view the results. Meshing commands issued from the command-line, or using dialogue boxes, do not cause the mesh to be automatically displayed. This way the experienced user can issue many commands before viewing the next picture. Furthermore, **True*Grid*®** does not have to recompute the mesh until a draw command is issued.

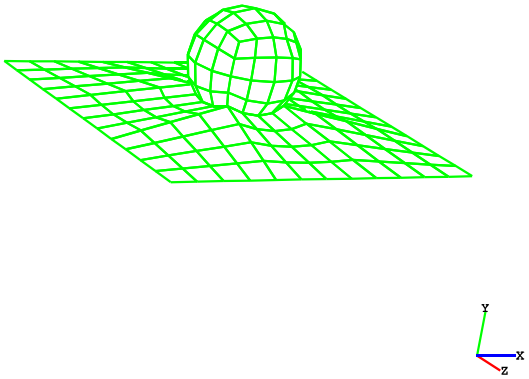
The Peel Commands

Before clearing the highlighting, try out the graphics peel commands. Select the **Display List** dialogue within the **Environment Window**. This is the same dialogue used to add and remove surfaces.



Press the **Region** button under the "Apply Action To" category. Then press the **Show Only** button under the "Action" category. **True*Grid*®** now shows only the highlighted selection. (Nothing has been deleted, only removed from the picture.) Because the current selection consists of the faces of the hole projected to the sphere, only these faces are shown.

Now clear the highlighting by pressing the **F2 KEY**. Activate the second dot on the j-index bar (corresponding to the second j-partition). While the **Region** button is still pressed, press the **Add** button in the "Action" category. The Physical Picture (which contains the actual mesh) appears as below.



Only Part of the Mesh

By activating only the second dot on the j-index bar, you selected the entire second j-partition. Then by pressing the **Add** button, you added this entire partition to the picture. Notice how easy it is to point to a region that is not in the picture and add it to the picture. With no other object is this possible. For in order to point to another type of object, that object must already be in the picture.

About the Mesh

Each of the 27 blocks is built the same way a single-block mesh is built.

First the corners of the block are positioned. Some corners are required to be on the sphere and others are not. Those required to be on the sphere **are projected to the closest point on the sphere relative to the corners initial position**. After all corners are positioned, then block edges are interpolated. This amounts to evenly distributing the edge nodes along a line connecting the corners. Edges required to be on the sphere are projected to the sphere. Next, edge nodes are used to interpolate face nodes. Faces required to be on the sphere are then projected to the sphere. Finally, interior nodes of each block are interpolated from the face nodes.

Notice that several blocks have some edges that are straight and others that are curved. The faces interpolated from these edges are not simple surfaces (i.e., non-planar).

* * * * * * * *

Because of the way True*Grid*® builds a block mesh, there is no need to specify intermediate surfaces and curves between the sphere and the outer walls.

* * * * * * * *

The True*Grid*® Challenge

This mesh was built with just FOUR commands. Try building a similar mesh using another mesh generator. Compare the time it takes and the mesh quality.

Mesh Diagnostics

Currently mesh diagnostics only exist in the Merge Phase. You cannot directly enter the Merge Phase without ending the current part. The commands

```
endpart merge
```

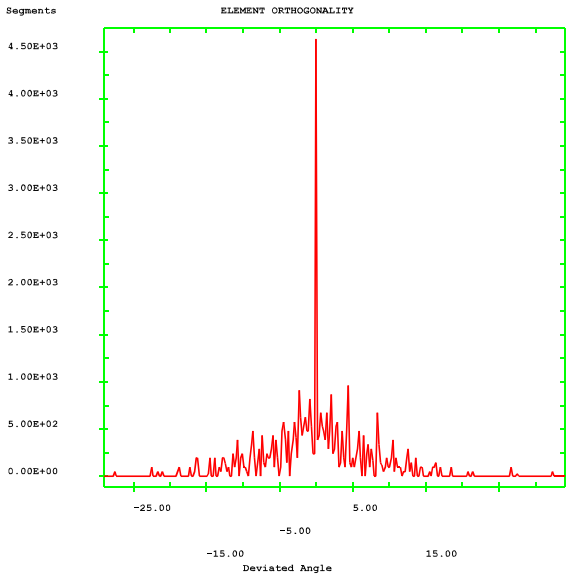
will end the part and switch **True*Grid*®** to the Merge Phase.

The computational window no longer exists because there may be several parts present in the Merge Phase. Also, nodes may be eliminated (merged) in this phase, thereby destroyed the correspondence between the computational and physical domains. No functions requiring the computational highlighting system are available, including the peel commands. Consequently, the entire mesh is displayed after a draw command.

The MEASURE Command

The **measure** command is in the **DIAGNOSTICS submenu**. Move to that submenu and locate the measure command. Press the left mouse button on the **MEASURE button** and a dialogue box appears.

In the measure dialogue, choose the **Orthogonal Test** option by pressing the left mouse button anywhere on the string. Execute the dialogue by pressing the **EXEC**ute button.



Orthogonality Test (*2D Curve* Window)

A new window whose title is *2D Curves* appears. In that window is a plot of the **deviation angle** (from 90 degrees) **vs.** the **number of segments**. The tallest peak is near 0, meaning that a substantial number of elements have nearly perfect 90 degree angles.

The absolute range of the test is printed in the text window:

```
measure ranges from
   -2.71598E+01 to
   3.249846E+01
```

indicating that the element angles are roughly between 62.5 and 122.5 degrees.

The ELM Command

The `elm` command is in the same DIAGNOSTICS submenu as the measure command. The `elm` command allows you to isolate elements whose measure is within a given range. Either use a dialogue box to specify a range between -28 -25, or directly issue the command

```
elm -28 -25
```

All the elements with angles between 62 and 65 degrees will be highlighted magenta. The part can be removed from the picture using the command

```
rp 1
```

Then only the selected elements remain in the picture.

Before trying another diagnostic command, add the part back to the picture

```
ap 1
```

This is necessary because **the measure command only measures those elements that the user has specified to be in the picture**. That is not to say only elements within the frame of the window are measured by this command, but all elements that are currently active and selected by the user.

To kill the 2D Curve Window, use the window manager "kill" or "quit" option for the window.

The Butterfly Mesh: Rounding a Corner

Putting a Square Peg into a Round Hole

Used in this example:

Multiple-Block Part
Region Deletion
Projection
Node Merging

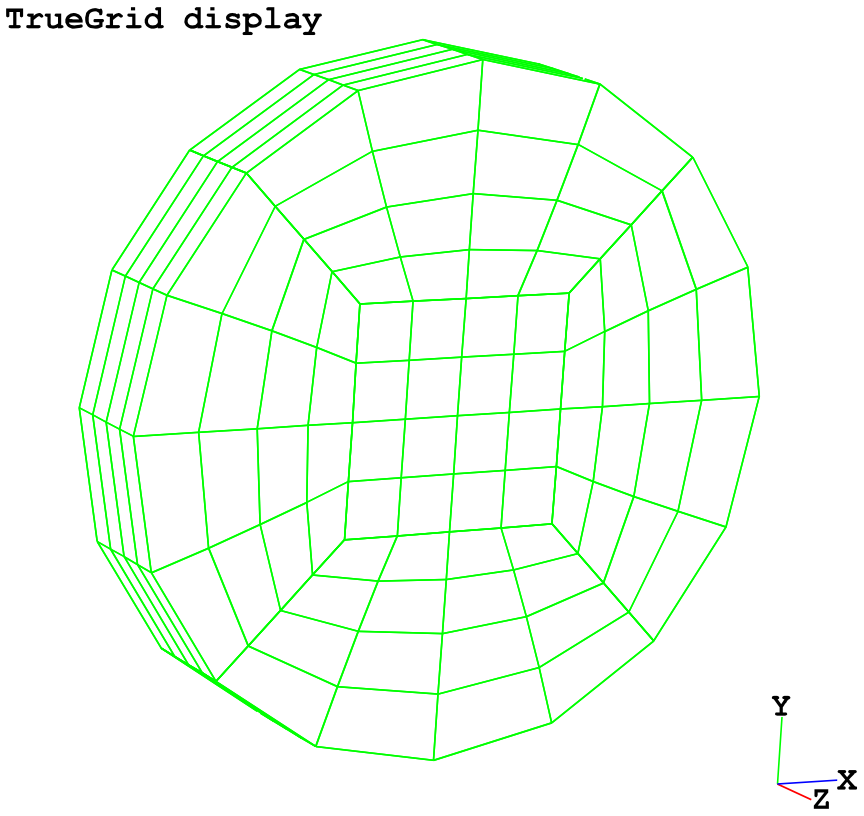
Prerequisites

Familiarity with interactive graphics and the previous multiple-block example.

Description

A technique is introduced for creating a good mesh of a rounded object using a block mesh in Cartesian coordinates.

The mesh is created using four commands.



The Butterfly Mesh, a.k.a. The Iron Cross

Creating the Part

Run **True*Grid***® with no input file. Create a 9-block part using the block command:

```
block 1  5 9 13; 1  5 9 13;1 5;
     -1 -1 1  1;-1 -1 1  1;0 1;
```

The resulting mesh contains several collapsed blocks. The first and second i-partitions have the same x-coordinates. Likewise, the second and third i-partitions have the same x-coordinates. An analogous statement is true for the j-direction and y-coordinate. All in all, only the center block of the mesh is not collapsed.

A good way to see that some regions are collapsed is to first draw both pictures and then explore the mesh using the **Slicing Plane** feature.

The Method

Notice that in the final mesh shown above there are only five blocks. The center block is easy to spot. Four other blocks surround this center block.

This mesh was created by first deleting the four corner blocks of the mesh. Then the outside faces of the four outside blocks were projected (in one command).

The Geometry

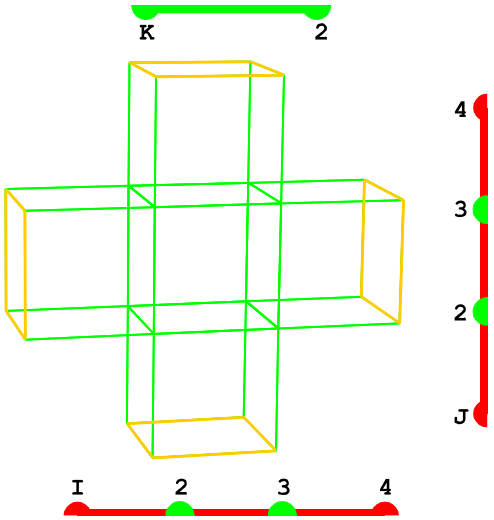
The geometry for this problem consists of a single right circular cylinder created with the following **S**urface **D**efinition command:

```
sd 1 cyli  0 0 0  0 0 1  3
```

(Extra spaces were added for the sake of clarity – you may omit these when entering the command.) This creates a cylinder of radius 3 whose axis passes through (0,0,0) and is parallel to (0,0,1).

Cutting Corners

All four corner blocks can be highlighted and deleted at once. Do this by activating the first and last segments of both the i- and j-index bars (these are on the lower and right window borders, respectively). Then press the **Delete** button in the environment window.



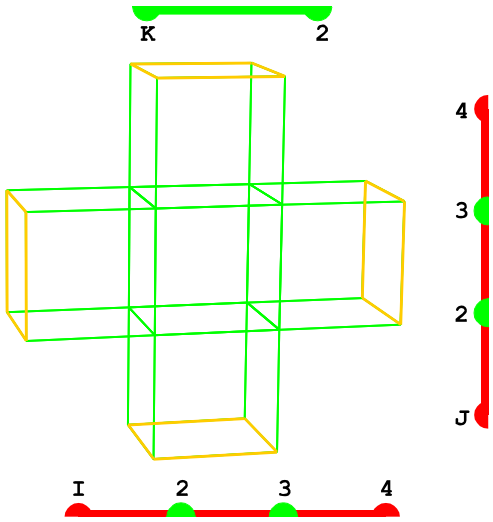
Delete the Four Corner Blocks

Projecting to the Cylinder

Clear the current computational selection by pressing either the **F2 KEY** or **CTRL+D**. Now activate all segments on both the i- and j-index bars. Activate all four endpoint dots of these index bars. This selection consists of four block faces.

Use the **Labels** dialogue of the **Environment Window** to label the surface. Use the **Pick** dialogue of the **Environment Window** to configure **True*Grid*®** to choose objects by label. Highlight the cylindrical surface by pressing the left mouse button on the label for this surface.

Finally, press the **Project** button in the **Environment Window** to project the four highlighted faces to the cylinder.



Faces Projected to the Cylinder

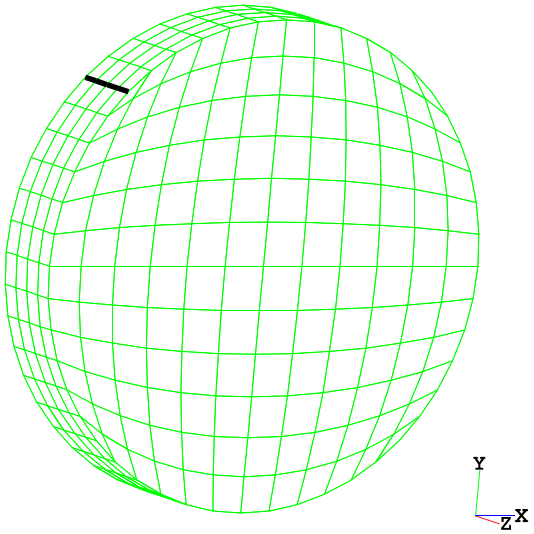
The mesh is finished, except for removing the redundant nodes on the block faces. To do this, end the part and change to the Merge Phase by issuing the commands

```
endpart merge
```

The redundant nodes are merged using the **S**tandard **P**art **T**olerance command

```
stp 0.01
```

View the merged nodes within the part using the graphics command `labels TOL 1 1.`



If the mesh is refined, then the problem just gets worse. This is because two points on a circle that are very close are connected by a segment whose slope is nearly the same as a tangent to the circle. Therefore, as the mesh is refined, the elements at the corner end up with two faces that are very nearly tangent to the cylinder. In other words, the two faces of the corner elements align themselves with a tangent plane to the cylinder (and, thus, with each other).

In general, the fact that the mesh quality actually goes down as the mesh is refined is a classic symptom of a bad topology. In these cases, the user should consider a different topology for the mesh.

A Square Peg in a Round Hole

The Reason for the Butterfly Mesh

The alternative to the butterfly mesh involves just projecting the blocks to the cylinder. Actually, the mesh could be a single-block mesh. Such a mesh is shown on this page.

Pay particular attention to the region near the corners of the block. The angles of elements in this region are not good.

One of the corners of the block has been darkened to illustrate what goes wrong with a mesh of this type.

The outer two faces of the block at a corner of the mesh must be folded back to conform to the cylinder. The result is that the elements near this corner have angles that are nearly 180 degrees.

Intersecting Pipes:
A More Challenging Problem

Intersecting Pipes

Used in this Example:

Technique of "Skinning" to build a Surface

Extracting Curves from Surfaces

Multi-Block Part

Interactive Placement of Regions of the Mesh

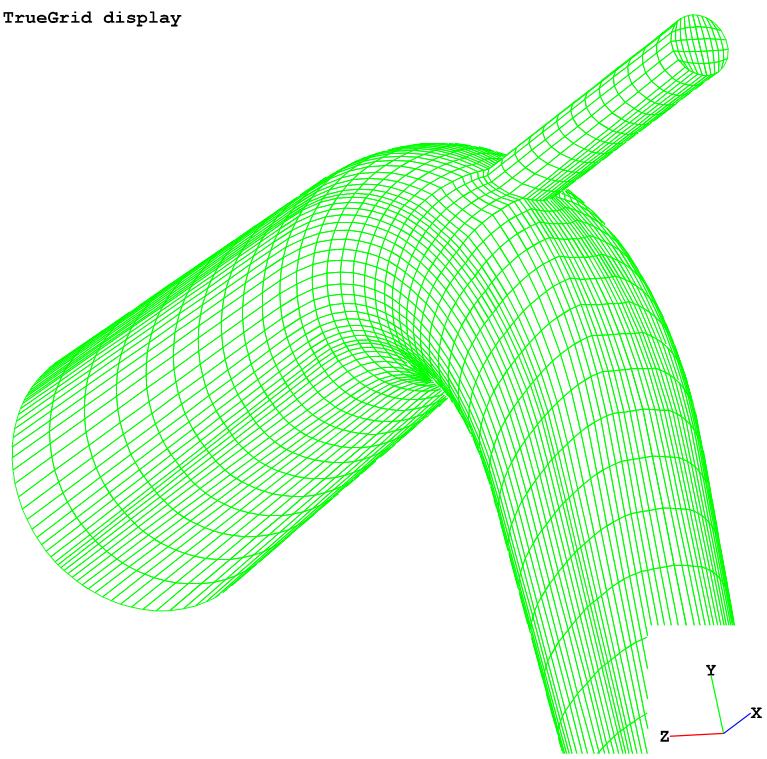
Interactive Placement of Mesh Edges on a Curve or Surface Edge

Interactive Mesh Refinement

Mesh Zoning

Part Replication

Node Merging



Intersecting Pipes with Node Clustering Toward Walls

Prerequisites

Familiarity with interactive graphics, menus, dialogue boxes, single- and multi- block part examples.

Description

The region inside two pipes that intersect is meshed. One pipe is an elbow pipe with varying cross-sections, and the other pipe is a cylindrical pipe.

Zoning is performed to cluster nodes toward the walls of both pipes.

The symmetry of the problem is exploited: only half of the model is constructed, and the other half is created using part replication.

The mirror image part and the original part are glued together to form the final model.

Getting Started

Run **True*Grid*®** with no input file. Enter the Merge Phase by typing the command

```
merge
```

followed by a return. This allows you to view the geometry for the problem as it is created.

The Geometry

The geometry for this problem is more complex than for previous examples. The elbow pipe is created using a technique of "skinning" whereby 2D cross-sections of the pipe are specified along a 2D curve.

A dialogue box for the 2D **L**ine **D**efinition command is accessed by moving to the **2D CURVE** submenu and then by pressing the left mouse button on the **LD** button.

Lists are sometimes too long to fit fully within the dialogue window. The Page Up, Page Down, Up Arrow and Down Arrow keys can be used to scroll. Or the arrows at the top can be used to scroll the text. Press the left mouse button on an arrow to scroll a page at a time. Press the middle mouse button on an arrow to scroll a line at a time. There is yet another option (for the dialogue box only): **press and hold the right mouse button down and drag the mouse vertically – the text will follow.**

An efficient way to use dialogue boxes is to first choose all applicable options using the mouse and then to enter all data using only the keyboard. So, first choose the

```
> Sequence of Coordinate Pairs
```

option by pressing the left mouse button anywhere on the entry.

Recall that the **red** character ">" preceding the entry indicates the option is part of an exclusive list. As soon as this option is chosen, the others disappear from sight, and the chosen entry is highlighted in **yellow**. Also recall that an option can be deselected by pressing the left mouse button on this entry again.

After the "Sequence of Coordinate Pairs" entry is selected, a prompt appears with a hollow green cursor. The cursor is hollow because this new input field is not the active input field.

Next, choose the entry

```
> Append Another Segment
```

This time, for the type of segment, choose

```
> Append an Elliptic Arc
```

There is another segment to add to this curve. So again choose

```
> Append Another Segment
```

The final segment is another polygonal segment. So choose the

```
> Append Sequence of
Coordinate Pairs
```

`Enter 1` for the curve definition number. Either press RETURN or the space bar. The space bar functions as a return because only one number can be entered in this field.

Enter two points for the first segment of the curve ((0,0) and (2,0)):

```
x1 z1 x2 z2 . . . :0 0 2 0□
```

The second segment is an elliptic arc:

```
length of first axis:1□
length of second axis:1□
x_center:2□
y_center:1□
beginning angle:-90□
ending angle:0□
```

Angle between the major axis and the x-axis

```
rotation:0□
```

The last segment is drawn from the last point of the elliptic arc to the final point:

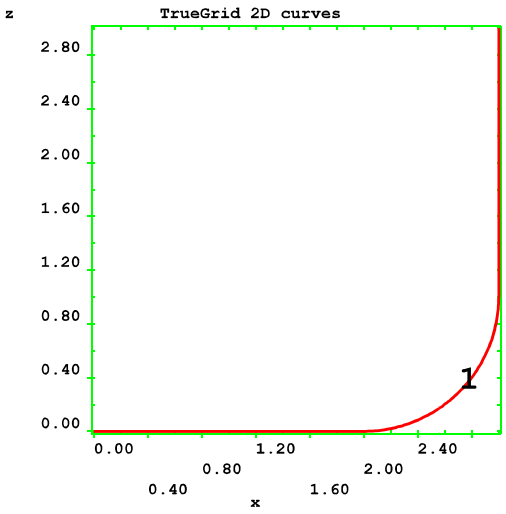
```
x1 z1 x2 z2 . . . :3 3■
```

Make sure to press RETURN after entering the final line (this checks for completeness).

Now press the **EXEC/QUIT** button.

The `lvi` command can be used to display the curve just created:

```
lvi 1 ;
```



The Sweeping Curve (Curve #1)

Curve 1 is used as a sweeping curve: Cross-sections of the pipe are defined perpendicular to and along this curve.

Two line definition commands define the cross-sections at the ends of the pipe. The curves are single elliptic arcs. Therefore, the option to choose in each of the next two dialogue boxes for the `ld` command is

```
> Append An Elliptic Arc
```

For the first of the two elliptic arcs, use line definition number 2, and specify the data as indicated below.

```
length of first axis:0.5□
length of second axis:0.5□
x_center:0□
z_center:0□
beginning angle:0□
ending angle:180□
```

Angle Between the major axis and the x-axis

```
rotation:0■
```

Press the **EXEC/QUIT** button to execute and quit this dialogue box. Now open another line definition dialogue box and choose the same options as before.

Assign line definition number 3 to this final elliptic arc. Enter the data for the line definition as shown below.

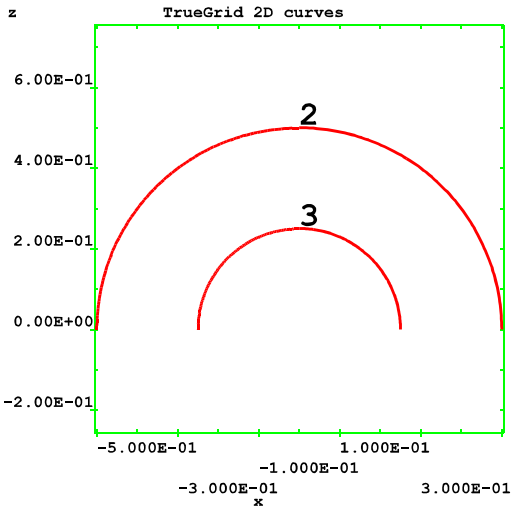
```
length of first axis:0.25□
length of second axis:0.25□
x_center:0□
z_center:0□
beginning angle:0□
ending angle:180□
```

Angle between the major axis and the x-axis

```
rotation:0■
```

View the two cross-sections with

```
lvi 2 3 ;
```



Cross-Sections at the Ends of the Elbow Pipe

To create the elbow pipe surface, use a dialogue for the **S**urface **D**efinition command. Press the left mouse button on the **SD** button in the **SURFACES** submenu to create the dialogue box.

Enter **1** as the **Surface Number**. Choose the option

```
> Sweep 2D Curves Along a
  2D Curve
```

The sweeping curve is curve definition 1.

```
sweeping 2D curve number:1□
```

Choose to place the cross-sections on the left of the sweeping curve by selecting

```
> Sweep on left side of
  sweeping curve
```

The final surface is formed by placing 2D cross-sections at various places along (and orthogonal to) the sweeping curve. The position of a cross-section along the sweeping curve is specified in terms of the arc length along the sweeping curve. The arc length is always normalized so that 0 corresponds to the first end and 1 to the other end.

```
number of 2D curve
       to be swept:2□
relative arc length
       position:0□
number of 2D curve
       to be swept:3□
relative arc length
       position:1□
```

No other cross-sections are needed for this surface. So choose

```
> End Swept Curve
  Surface Definition
```

True*Grid*® will smoothly interpolate between specified cross sections. The cross-sections of the swept surface are both semi-circles and, so, the interpolated cross-sections will also be semi-circles.

Apply a transformation to the swept surface to bring it into position. Under "LIST OF TRANSFORMATIONS" choose

```
> Rotate about the x-axis
```

and specify a rotation angle of -90 degrees:

```
angle (degrees):90■
```

Execute and quit the dialogue to define the upper half of the elbow pipe surface.

There are two more surfaces to be defined: a cylinder and a plane of symmetry. Define these surfaces using a dialogue box or by typing these commands:

```
sd 2 cyli  0 0 0  1 0 0  .1
sd 3 plan  0 0 0  0 0 1
```

Surface 2 is a cylinder of radius 0.1 whose axis is parallel to (1,0,0) and passes through (0,0,0). Surface 3 is a plane passing through (0,0,0) and whose normal is parallel to the vector (0,0,1).

Extracting Curves from Surfaces

It is sometimes convenient to have a curve along which to position an edge of the mesh. In many such cases, a contour of a surface used primarily for graphical purposes turns out to be nearly ideal. Such contours can be converted to 3D Curves in **True*Grid*®** for just such a purpose.

When a contour used for graphical purposes is converted to a curve, all points on that curve are written to the session file. This is because the way that **True*Grid*®** tiles a surface for graphical purposes may vary between versions. However, writing all points of the curve to the session file creates a permanent record of the curve.

The variation in graphics also creates a problem in describing how to locate the surface contours used in this example. Our solution is to specify some 3D line segments that serve as markers. The user is then asked to locate surface contours ending near these markers.

Create the markers for this problem with the 3D **CUR**ve **D**efinition command (**curd**). Two such markers are required:

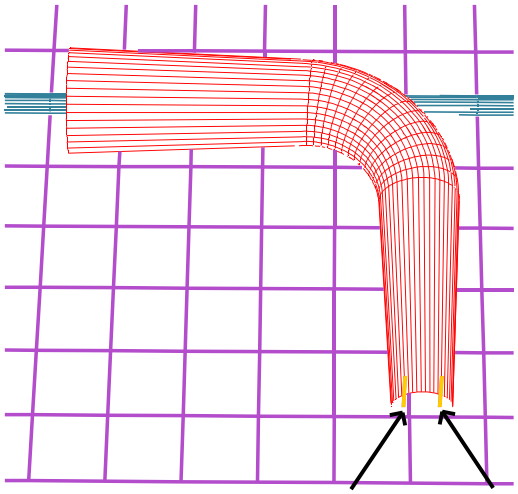
```
curd 3 lp3 3.1433942 -3 0.5
           3.1433942 -3 0;;
curd 4 lp3 2.8495464 -3 0.5
           2.8495464 -3 0;;
```

These commands define segments joining two 3D points. The segments should align with the endpoints of certain contours on the elbow pipe. (However, do not be alarmed if the alignment in this version is not so precise.)

Make sure all surfaces and curves are displayed: use either the **Display List** dialogue in the Environment Window or

```
dasd dacd
```

The alignment marks are yellow and are located at the lower end of the elbow pipe.



Arrows Point to Alignment Marks

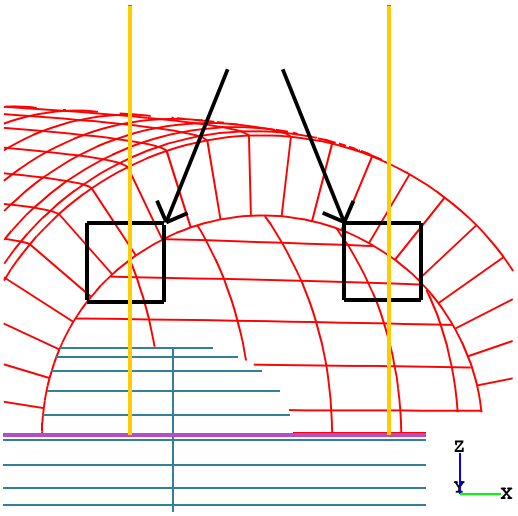
Visual alignment is required in this example. The effects of perspective are detrimental to such alignment. So turn perspective off with

```
angle 0
```

Frame the lower end of the pipe by issuing these graphics commands:

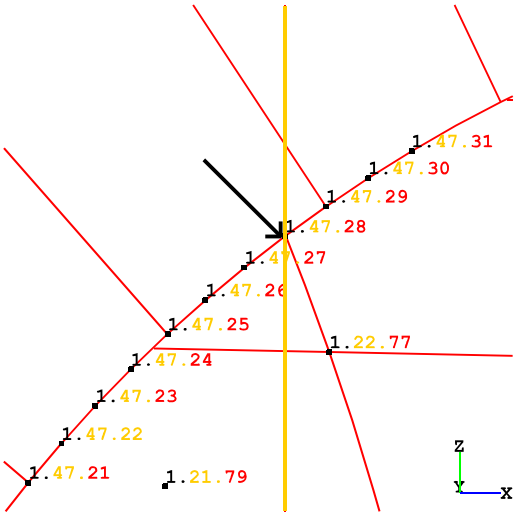
```
REST RX -90 L 0.19 ZF 12
```

The REST command puts the picture in a default position first. The other commands **R**otate the picture about the **X**-axis, translate the picture **L**eft and **Z**oom **F**orward.



A Close-Up of the Lower Pipe End

Use the **Frame** graphics option to isolate the intersection of the left alignment marker with the semi-circular edge of the elbow pipe surface. Display the labels of points on defined surfaces (press the **Surf Point** button in the **Labels** dialogue of the Environment Window).



Surface Point Labels Near the Left Alignment Mark

The point corresponding to a label is indicated with a small "┼". Choose the label of the point on the surface edge nearest the vertical alignment mark. For the version of **True*Grid*®** used while making this tutorial,

the alignment mark intersects the surface edge at a point whose label is

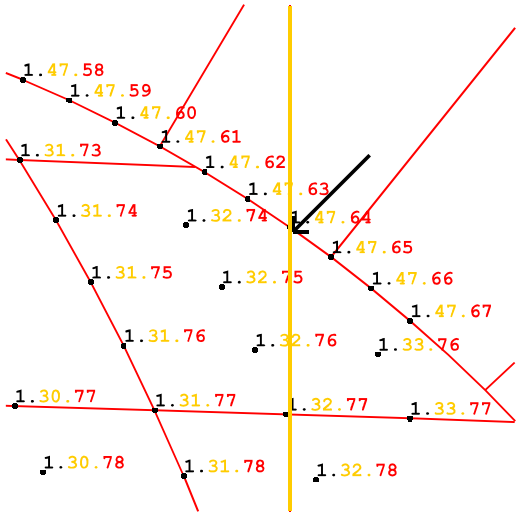
```
1.47.28
```

Make a record of the label number you found.

Use the **Move** graphics feature of **True*Grid*®** to move the picture left until the yellow alignment mark on the right appears.

Choose the label of the point on the edge of the elbow pipe surface nearest the vertical alignment mark. For version 1.1.0 of **True*Grid*®**, the alignment mark intersects the surface edge at a point whose label is

```
1.47.64
```



Surface Point Labels Near the Right Alignment Mark

Notice these labels have two components in common. The first part of the label is the surface definition number (in this case 1). The second and third parts are indices into a grid of points used to draw the surface. Both points lie on a common edge of the surface and, therefore, have the same value for one of the last two indices.

The corresponding points on the other end of the elbow pipe surface have labels

```
1.1.28  and  1.1.64
```

The two curves we wish to construct lie on the elbow pipe surface and have endpoints with labels 1.1.28, 1.47.28 and 1.1.64, 1.47.64, respectively (these numbers may depend on the version number of **True*Grid*®**).

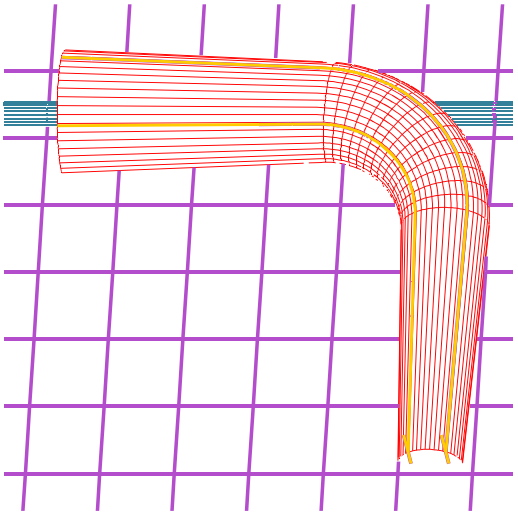
The required 3D curves are created with two applications of the `curd` command:

```
curd 1 contour 1.1.28 1.47.28;;
curd 2 contour 1.1.64 1.47.64;;
```

Alternatively, use a dialogue box for the `curd` command (located in the **3D CURVE** submenu). Choose the dialogue box option

```
> Begin With A Surface Contour
```

The 3D curves just created are shown below. The "contour" curves are darkened for emphasis. These 3D curves appear yellow on the computer screen.



The Final Geometry (3D Curves are Darkened)

Making the Part

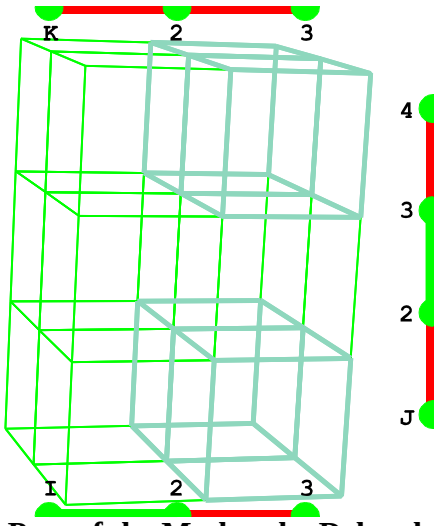
The block command for this example may seem unusual at first because all coordinates are set to 0.

```
block 1 2 3;1 2 3 4;1 2 3;
      0 0 0;0 0 0 0;0 0 0;
```


The mesh will be interactively positioned; so initial coordinates do not matter. Notice that each block is only one element thick. Elements will be added later.

The physical picture of the mesh is not very interesting because the entire mesh is collapsed to a point, namely (0,0,0).

The first two mesh commands delete portions of the mesh. First highlight the region shown and press the **Delete** button in the environment window.

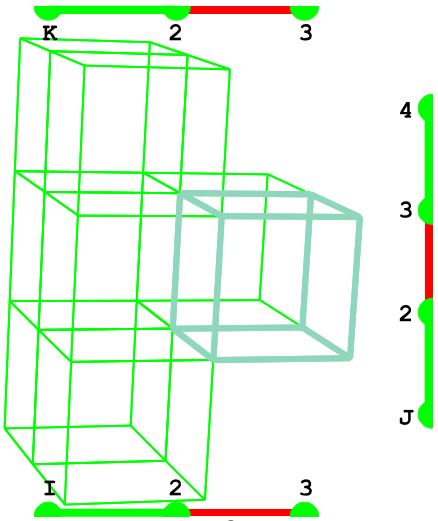


First Part of the Mesh to be Deleted

There is a curious feature of the computational highlighting that should be mentioned. If no dots or segments along an index bar are activated, then **True*Grid*®** treats this the same as if all segments were activated and all dots were not. Consequently, activating all segments in the k-direction (as shown above) is the same as activating none. All segments were activated here for clarity only.

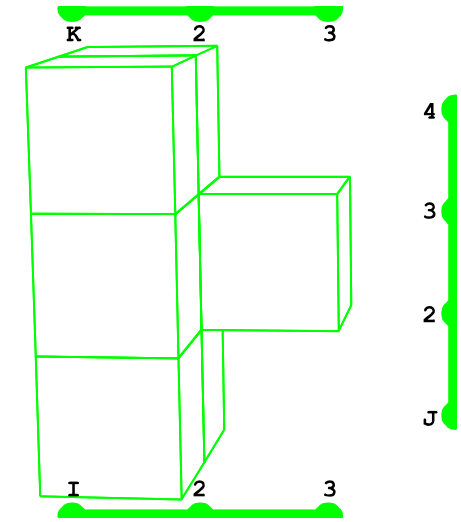
There is one other curiosity concerning the highlighting: If nothing is activated in any direction, then this is equivalent to having chosen all solid blocks. However, the highlighting does not indicate this (otherwise there would be no way to remove all highlighting). But be aware that using a NULL selection will cause the command in which the selection is used to be applied to all solid blocks. So, for example, pressing the **Delete** button when the selection is NULL causes the entire mesh to be deleted!

There is only one other piece of the mesh to be deleted. That piece is pictured below.



The Other Part of the Mesh to be Deleted

The final computational block structure is shown below.



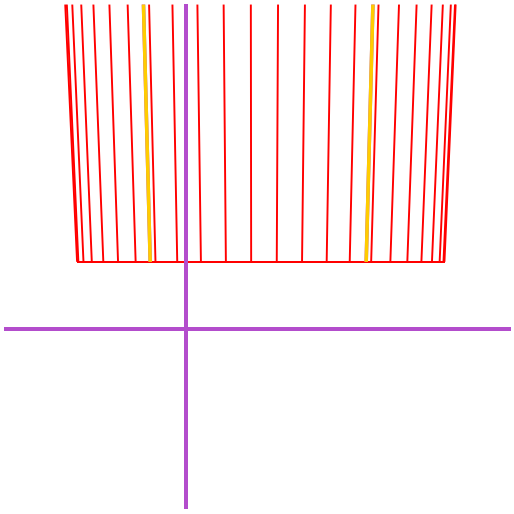
Final Computational Picture

The next stage of building this mesh requires interactively moving parts of the mesh so that it resembles the final shape.

Bottom faces of the bottom blocks are positioned first, near the bottom end of the elbow pipe. Use either the **Frame** option to focus on the lower end of the pipe, or the commands

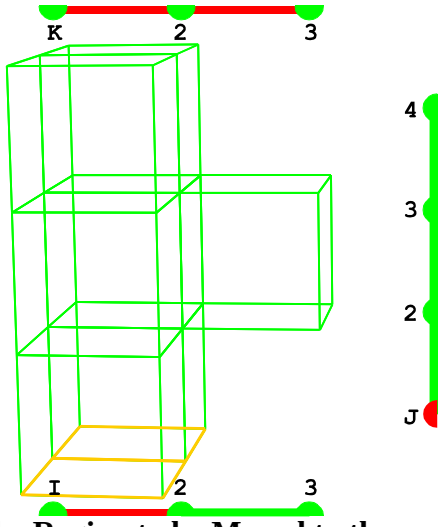
```
REST L 0.19 U 0.25 ZF 10
```

These graphics commands roughly center the lower edge of the elbow pipe in the picture.



The First Interactive Move involves the Lower End of the Elbow Pipe

The region to be positioned along the edge of the lower end of the elbow pipe needs to be highlighted (pictured below).



The Region to be Moved to the Lower End of the Elbow Pipe

The "Move Pts" Dialogue Box Controls how Interactive Positioning is Done

The left mouse performs several different functions in the Physical Window such as selecting an object by label, selecting the nearest vertex, and moving regions. All functions performed with the left mouse are indicated by a picture of the mouse with an "X" over the left button.

Set up **True*Grid*®** so parts of the mesh can be moved interactively. To do this, press the **Move Pts.** button in the Environment Window. The dialogue shown above appears.

WARNING: Be careful while **True*Grid*®** is configured to move points of the mesh. Pressing the left mouse button while in this mode can cause trouble. Use the **Undo** button to deactivate an unintended move command.

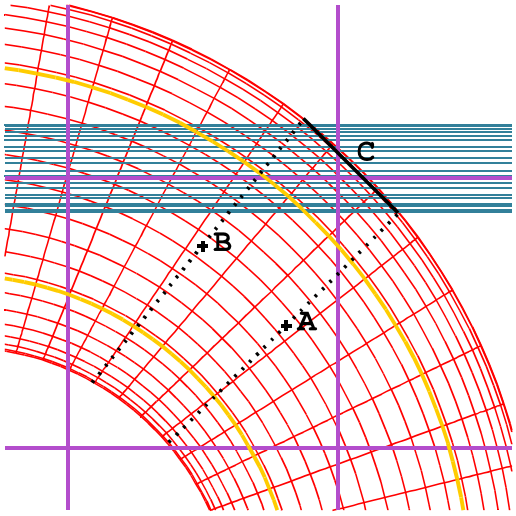
The object is to move the previously highlighted region to the center of the lower edge of the elbow pipe. Choose the **Screen Plane** option for this example. This option is used to restrict movement of the points to plane(s) parallel to the screen plane.

Now press and hold the left mouse button down in the physical window. As soon as the mouse is moved, a cross hair appears and a line is drawn from the center of the highlighted region to this cross-hair. The highlighted region is redrawn centered at the new cross-hair. Move the mouse until the cross-hair is centered along the lower edge of the elbow pipe. Release the mouse button.

All of the mesh, except for the two faces just repositioned, is still sitting at the origin. The two highlighted faces are still collapsed to a single point, just a different point than the remaining part of the mesh. The edges between the highlighted faces and the remaining part of the mesh are interpolated automatically. So the mesh *appears* to be a single line segment.

Next, faces of the mesh are positioned near the bend of the elbow pipe. These graphics commands center the elbow of the pipe in the picture:

```
REST L 0.15 D 0.15 ZF 6
```



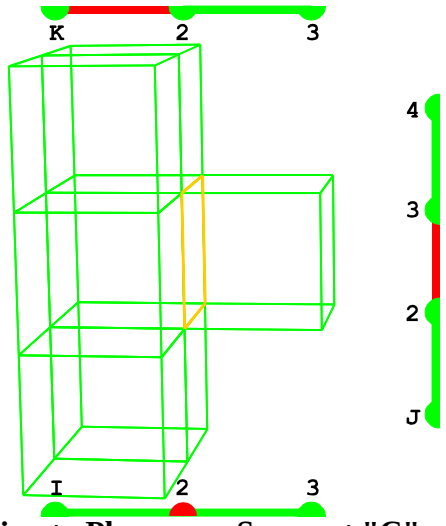
Just Around the Bend

Modify the computational selection just used by activating the second dot along the j-index bar instead of the first. (The dots and segments toggle on and off. So, turn the first dot on the j-index bar off by pressing the left mouse button on that dot again.) Use the

Screen Plane option again to reposition the new region near Point "A" (shown above).

The next region of interest is obtained by modifying the current selection so that the third dot on the j-index bar is activated instead of the second. With the **Screen Plane** option still in effect, reposition the new region near Point "B" (shown above).

The **Screen Plane** option is also the appropriate option for the next command: Highlight the single block face shared by the larger and smaller rectangular blocks of the mesh. Move this region so that it nearly aligns with Segment "C" shown above.

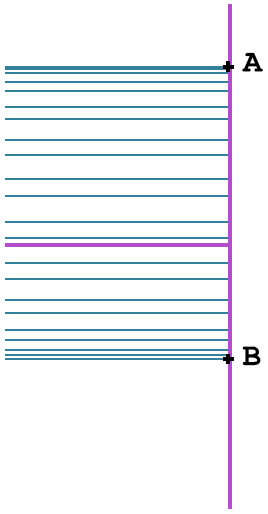


Region to Place near Segment "C"

Because blocks of the mesh are being pulled apart now, the mesh is no longer one-dimensional.

The final interactive positioning commands are used to initialize the isolated block of the mesh near the cylindrical pipe.
Issue these graphics commands to center the right end of the cylindrical pipe in the picture:

```
REST L 0.355 D 0.175 ZF 20
```



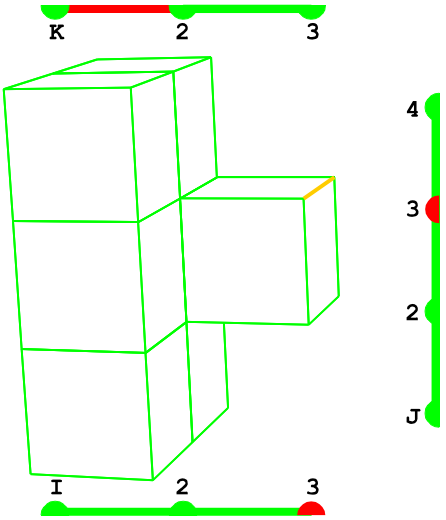
Right End of the Small Pipe

The resulting Physical picture is shown below.

The goal is to position the edges on the right side of the isolated block of the mesh around the perimeter of the cylindrical pipe.

An edge of the mesh is highlighted when a single dot is highlighted on each of two index bars, and when only segments are highlighted on the other index bar. The two dots determine two planes. The intersection of the two planes is an edge. Choosing segments in the other direction serves to restrict the edge. Many mesh edges can be selected at once, but all edges in a single selection must be aligned in the same direction. **Mesh edges are highlighted blue**.

The first edge to be moved is pictured below. Use the **Screen Plane** option to position this edge near Point "A" of the previous diagram.



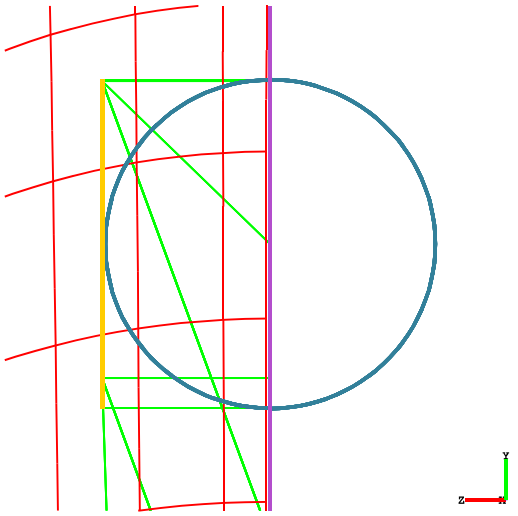
Position this Edge Near Point "A"

Highlight the next edge to be moved by altering the current selection: deactivate the third j-index dot and activate the second j-index dot instead. Use the **Screen Plane** option, and position this edge near Point "B".

All points of the mesh still lie on one plane. The final interactive repositioning will move the region around the smaller pipe away from this plane. So issue the graphics commands

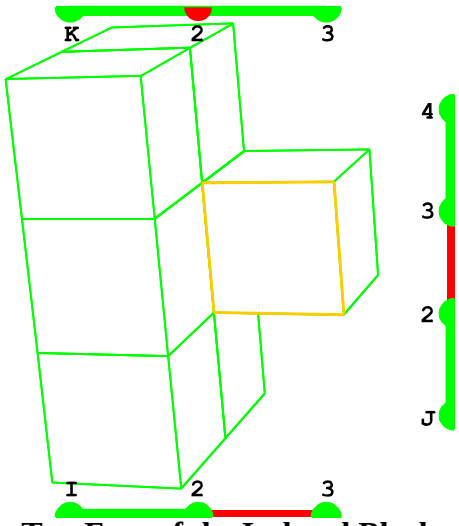
```
REST RY -90 L .025 D .16 ZF 25
```

to produce a picture looking straight down the cylindrical pipe.



Looking Down the Cylindrical Pipe Toward the Elbow Pipe

Highlight the top face of the isolated block of the mesh. This face lies on the second k-partition, between the second and third i-partitions and between the second and third j-partitions.



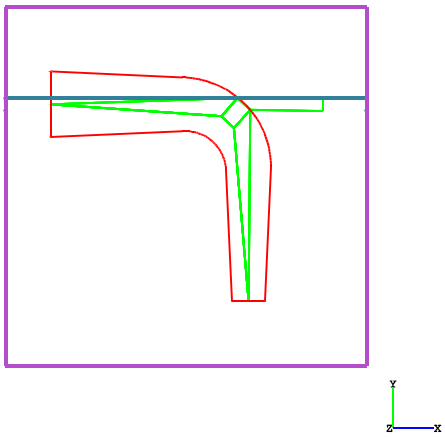
The Top Face of the Isolated Block

The picture looking down the end of the cylindrical pipe shows the desired position of the final mesh. Notice in particular the darkened line. This is the desired position of the face that is currently highlighted.

Choose the **Z** option for moving the region instead of the **Screen Plane** option. This option allows points only to move parallel to the global z-axis (notice the triad). Proceed to reposition the highlighted face.

Put the mesh back in a rest position. Turn off the display of interior lines of the surfaces by issuing the command

```
sdint off
```



The Mesh So Far

Note that the curves have also been removed from the picture for the sake of clarity.

Positioning Edges of the Mesh Along Curves and Surface Edges

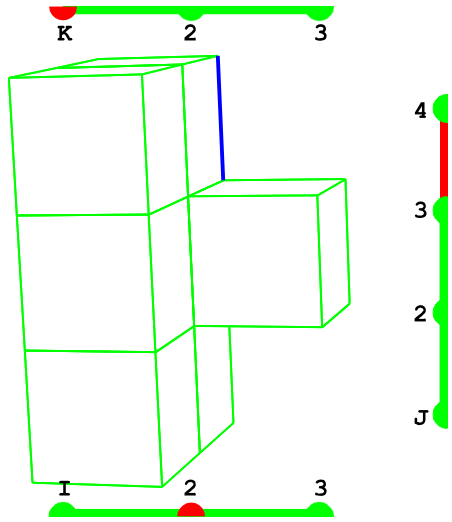
The next commands position certain edges of the mesh along curves or surface edges.

The `sdint off` command just issued shows just the edges of the surfaces. It is not necessary to issue this command to position mesh edges along surface edges--in this case, it just cleans up the picture.

Using the **Labels** dialogue of the **Environment Window**, choose the option to label all surface edges by pressing the **Surf Edge** button. Reconfigure **True*Grid*®** to choose objects by label. This is done by pressing the **Label** button in the **Pick** dialogue of the **Environment Window**.

Highlight surface edge `1.3`. This is the upper edge of the elbow pipe.

Now highlight the mesh edge shown below.



Edge to be Initialized to Edge 1.3

Press the **Attach** button and **True*Grid*®** will reposition the nodes of the selected edge along the highlighted surface edge.

Right now there are no intermediate nodes along the highlighted edge (this will change). So only the endpoints can be repositioned.

The next edge is highlighted by modifying the current selection: deactivate the segment between the third and fourth dots of the j-index bar, and active the segment between the second and third dots of the j-index bar. This can be done in one step because segments toggle on and off: press the mouse on the fourth dot of the j-index bar and drag the mouse to the second before releasing the mouse. This toggles the top segment off and the next-to-top segment on.

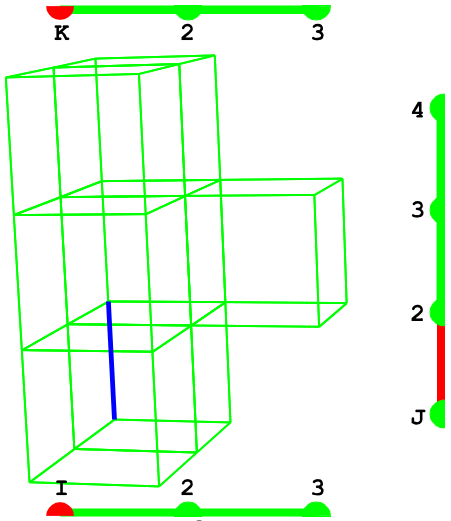
Select surface edge `1.3` again, and press the **Attach** button.

Modify the current selection again by deactivating the j-index bar segment and activating the j-index bar segment from the first j-partition to the second. Attach this edge to surface edge `1.3` as well.

You may be wondering why it is not possible to issue just one command to attach all three edges to surface edge `1.3`. Actually, this is possible. However, doing so would not yield the intended effect.

Issuing the command for all three edges at once would cause **True*Grid*®** to treat the three edges as though they were part of a single block. In particular, **True*Grid*®** would evenly distribute all nodes of the composite edge along surface edge `1.3`.

Breaking the attach command into three commands causes **True*Grid*®** to deal with each block edge separately: the endpoints of the edge are moved to the closest point on the surface edge (i.e., projected), and all intermediate edge points are evenly spaced along the surface edge. The nodes along the composite edge do not end up evenly spaced along the surface edge.



Attach to Surface Edge 1.1

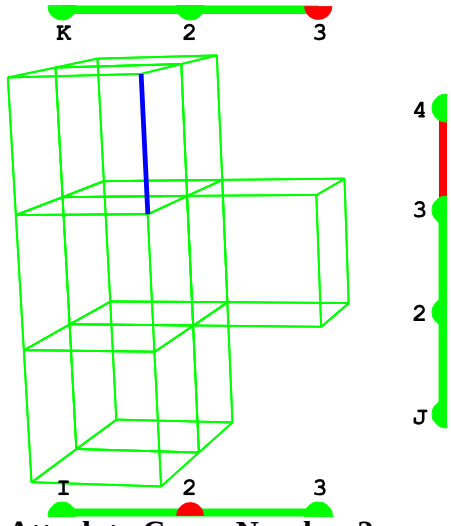
It is possible to attach the composite edge all at once and then use the double re-spacing command to reposition the nodes. But this would be more trouble than issuing three separate attach commands.

Next attach the three edges on the opposite side of the large rectangular block to surface edge `1.1` beginning with, for example, the edge shown below.

Half of the attach commands are finished. The remaining 6 attach commands involve curves instead of surface edges. So make sure all curves are showing (use the **Display List** dialogue box of the **Environment Window**). And, label curves instead of surface edges using the **Labels** dialogue box of the **Environment Window**).

Attachments will involve only curve definitions 1 and 2. The other two curves were for alignment purposes only.

Begin by attaching the edge pictured below to curve number 2.



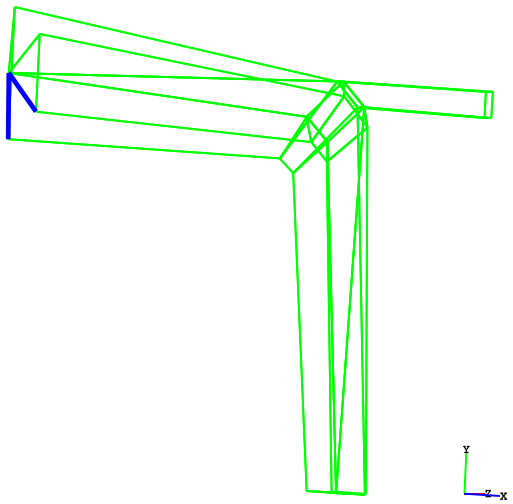
Attach to Curve Number 2

The situation here is analogous to the previous, where three block edges were attached to a surface edge. Attach to curve definition 2 the remaining two block edges of the top right edge of the large rectangular region.

Now attach to curve definition 1 the three edges along the top left edge of the large rectangular region.

Interpolation of Intermediate Edges

The mesh constructed so far is shown below. Notice the highlighted portion in the picture. This is the composite edge of the mesh formed by intersecting the first i-partition and the last j-partition. The reason this segment is not well-positioned is that little has been done to the block corners along the second k-partition. Most corners along the first and third k-partitions have been positioned along curves or surface edges.



The Mesh After All Attach Commands

This points out a major difference between a single block mesh and a multiple block mesh: interpolation is not automatically performed across block boundaries, only within each block.

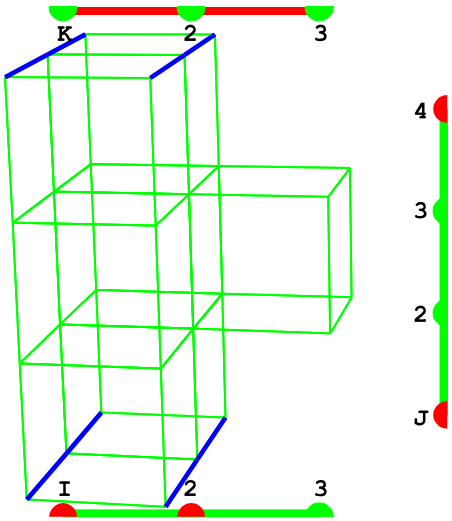
The solution is to apply interpolation to composite edges. To do this, first highlight the edges shown below.

Then type

```
lini
```

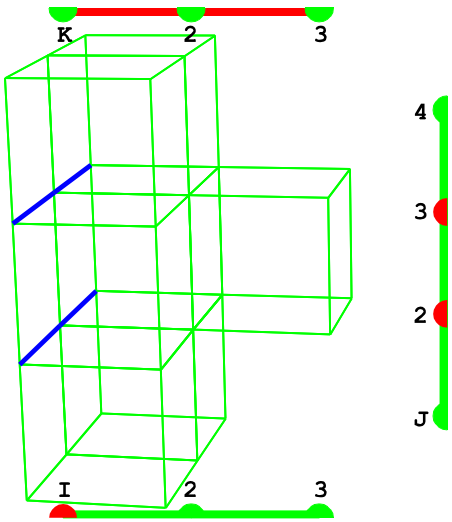
on the command line and press the **F1 KEY** or **CTRL+A** to convert the current computational selection to a numerical description. The command line will now be

```
lini -1 0 -2;-1 0 -4;1 3;
```



Composite Edges to be Interpolated

Before issuing a draw command, carry out the same procedure for the highlighted region in the next picture as well.



Composite Edges to be Interpolated

Now issue a draw command for the Physical Window. Notice that there are no degenerate regions remaining.

There is one more linear interpolation command that will be useful. The need for this command will be obvious once more nodes are added.

It's time to Project

The initial position of the mesh largely dictates the node distribution of a mesh after a projection. The projection command, in rough terms, snaps nodes to the closest point of the surface to which the nodes are projected.

Though over-simplified, this explanation helps one to understand why the initial position of the mesh before projection affects the final node distribution. For example, two nodes that start at the same position will (after a projection) end up in the same position. Also, if a mesh is initialized non-symmetrically about a symmetric object, the resulting mesh will not be symmetric.

The first projection command places the bottom of the mesh (first k-partition) onto the plane (surface definition 3). The command

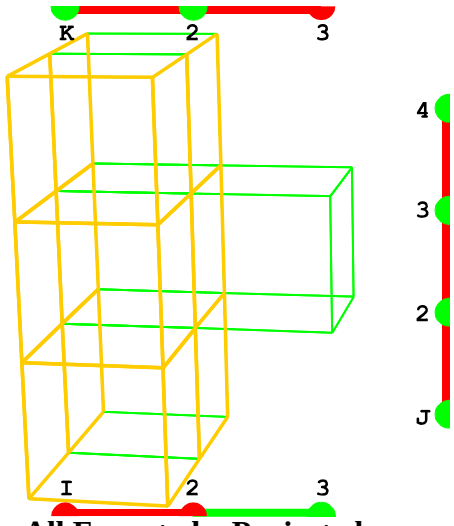
```
sfi ; ;-1; sd 3
```

will perform this projection. A draw command is not automatically issued when the projection command is typed.

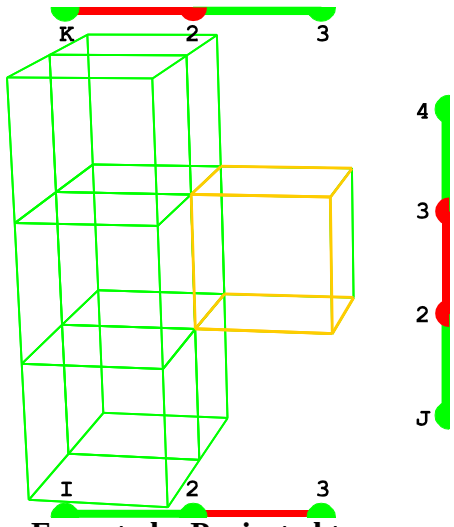
Recall that projections can also be done using point-and-click: highlight the faces to be projected, highlight the surface onto which the faces are to be place, and press the **Project** button. A picture is automatically redrawn.

Surfaces must be displayed and labeled to perform interactive projections. Use the **Display List** dialogue to put all surfaces into the picture, and the **Labels** dialogue to label all surfaces. Make sure the **Label** button in the **Pick** dialogue is set; otherwise, left mouse button presses to highlight a surface by label may be misinterpreted.

Highlight surface number 1, the region shown below, and press the **Project** button. Notice if only the segments were activated, the selection would consist of all blocks within the largest rectangular piece of the mesh. Once dots are activated, the selection will consist only of block faces. Three of the six collections of block faces surrounding this rectangular piece have been selected. This is a standard technique for selecting multiple block faces.



All Faces to be Projected to the Elbow Pipe



Faces to be Projected to the Small Cylindrical Pipe

Use the same procedure to highlight the block faces to be placed on the cylindrical pipe. Then highlight surface number 2 and press the **Project** button. As a check, this region is pictured below.

Adding More Nodes

Two things are required to finish the mesh: add some nodes and issue re-spacing commands to cluster the nodes near the walls of the pipe.

Nodes should be added before clustering is done; otherwise, the effects of clustering commands will hardly be noticed. Just how many nodes to add is a question of the simulation to be performed. We add 15 nodes to two ends of the elbow pipe in the direction of the pipe (j-direction), and add 2 nodes to the center section of the elbow pipe. This is done using the command

```
mseq j 15 2 15
```

(The mesh is not automatically redrawn.) Next we add 15 nodes across the pipe and 10 nodes along the length of the cylindrical pipe using the command

```
mseq i 15 10
```

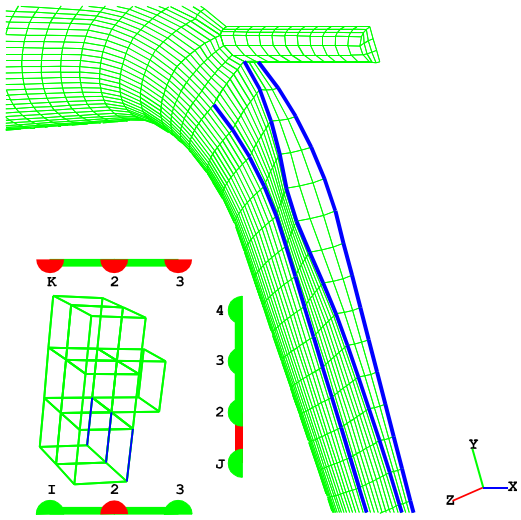
Finally, add 2 nodes to the bottom section of the pipe (and, consequently, 2 to the entire cylindrical pipe) and add 8 nodes to the top section with the command

```
mseq k 2 8
```

Issue a draw command to see the refined mesh. A hidden line version of the picture is probably called for. The surfaces will interfere with such a picture. Therefore it is best to first remove all the surfaces using the **Display List** dialogue in the **Environment Window**. On the other hand, you may wish to leave the surfaces in the picture to convince yourself that the faces projected to the pipe surfaces are actually projected.

It will take some time to see the new picture because the mesh must be rebuilt, and now there are many more nodes in the mesh.

The need for another linear interpolation command becomes apparent at this time, now that there are many more nodes. Notice that the node distribution on the block faces pictured below is not ideal (the edges of these block faces are darkened).

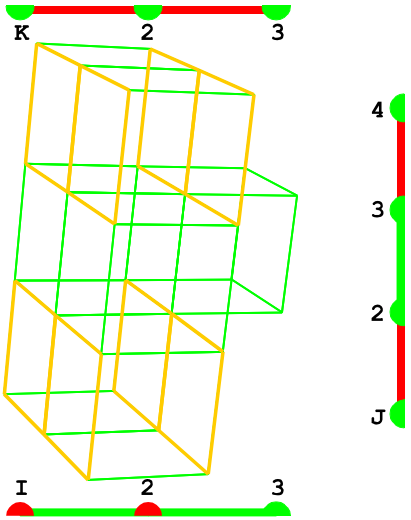


What happened. Of the three darkened edges shown above, only the two outside edges were positioned. One was placed along a curve and the other along the edge of the elbow pipe surface. The middle edge was positioned (before projection) using the default interpolation. Therefore, the middle block edge was, before projection, a straight line segment connecting a point somewhere on the bend of the pipe to a point on the lower end of the pipe. (You can see this by deactivating the projection command of faces onto the elbow pipe. Be sure to reactivate the command afterwards.)

Projection moved each node on the intermediate edge to its closest point on the elbow pipe. Nodes that were well inside the pipe were, therefore, moved closer to the top of the elbow pipe.

The way to correct this situation is to apply an interpolation command across the two block faces sharing the intermediate edge. Then **True*Grid*®** will treat the two faces as though they were one block face, and the intermediate edge will be interpolated between the two outer edges before projection. Then because the nodes of the combined face are all rather close to the pipe, the final distribution of nodes is much nicer.

Actually, there are four composite faces of the mesh that can benefit from additional interpolation. Highlight the faces pictured below, and issue the `lini` command for these faces (use the F1 Key to convert the selection to a numeric representation).



Composite Faces to be Interpolated

The final interpolation command is

```
lini -1 0 -2;1 2 0 3 4;1 3;
```

Clustering Nodes near the Pipe Walls

The Re-spacing command was discussed in the context of the single-block example. Recall that this command is used to space nodes in a particular direction in such a way that the ratio between adjacent pairs of nodes in the specified direction is a given number.

The re-spacing command only applies to mesh edges. A re-spacing command for a face or a solid is converted to several re-spacing commands for all the edges in the face or solid.

If a re-spacing command is applied to a composite edge, then intermediate block corners on the composite edge are also re-spaced. In this regard, the re-spacing command is the same as the linear interpolation command.

When a re-spacing command is applied to an edge, the nodes are reshuffled along the current curve of the edge. This means, in particular, that re-spacing will not change the "shape" of the curve on which the edge nodes currently lie. By contrast, recall that the linear interpolation command can be used to changed the shape of an edge (we used the `lini` command to change the shape of an intermediate edge earlier).

The linear interpolation command can be used to determine the shape of an edge, and then the re-spacing command to determine the distribution of nodes along that edge.

An edge positioned along a curve or surface edge can also have a re-spacing command applied to it. Then nodes will be distributed along the curve or surface edge in such a way that they obey the zoning law.

An edge that must lie on one or more surfaces (due to projection) can also have a re-spacing command applied to it. In such a case, both the projection and re-spacing requirements will be satisfied.

All these considerations together show the versatility of the re-spacing command. The interaction of this command with others is quite sophisticated and, yet, natural.

Now, highlight the largest rectangular section of the mesh by highlighting only the segment between the first and second i-partitions. Next type `res` on the command line, press the F1 Key to convert the selection to a numeric description, and add `"k [1/1.1]"` to the command line to obtain

```
res 1 1 1 2 4 3 k [1/1.1]
```

Square braces (`[ ]`) are required whenever an expression involving arithmetic or FORTRAN functions is issued.

To save time, issue more re-spacing commands before drawing the picture.

The current `res` command zones the edges of the region inside the elbow pipe in the k-direction (i.e., from the symmetry plane to the

top of the pipe). As k increases, the distance between nodes decreases (the specified ratio is less than 1). Consequently, the nodes cluster toward the "top" wall of the pipe.

Next, restrict the current selection in the j-direction to the top third of the blocks. That is, highlight the j-index bar segment between the third and fourth j-partitions. This time, apply the `res` command in the j-direction with a ratio of `1.1`.

```
res 1 3 1 2 4 3 j 1.1
```

This command causes nodal distances to increase with increasing j. Thus, nodes cluster near the elbow in the upper section of the elbow pipe.

Now apply the re-spacing command to the lower third of the blocks in the elbow pipe. Use a ratio of `1/1.1` to cluster oppositely.

```
res 1 1 1 2 2 3 j [1/1.1]
```

This command also causes nodes to cluster near the elbow because nodal distances decrease from the bottom of the pipe to the elbow.

Now apply the double re-spacing command to the entire region of the elbow pipe. This time the clustering is done in the i-direction to cluster nodes toward the sides of the pipe. This command requires two ratios. Use `1/1.2` for both ratios:

```
drs 1 1 1 2 4 3  i  1.2 1.2
```

The first ratio causes distances to first increase with increasing i. The second ratio has the opposite effect on the opposite side. Therefore, nodes cluster toward the sides, near the pipe walls.

The last re-spacing command is another double re-spacing command. This time highlight the middle third of the blocks of the elbow pipe. Further restrict this selection to those about the cylindrical pipe (i.e., between the second and third k-partitions). Use a double re-spacing command to cluster nodes both toward the top of the pipe and toward the top of the cylindrical pipe:

```
drs 1 2 2 2 3 3  j  1.2 1.2
```

Now draw the new picture.

Note: Remember that clustering commands are translated to commands for edges. Therefore, these commands can be order-dependent: the last re-spacing command applied to an edge is the one that ultimately applies.

Further Suggestions

Clustering could also be done within the smaller cylindrical pipe.

The mesh in the pipes suffers from the same defect illustrated in the section *Putting a Square Peg in a Round Hole*. An example of a "double butterfly" mesh is shown at the end of this section. The butterfly mesh is much better near the boundaries of the pipes. However, some simulation codes cannot deal with the complicated structure of the double butterfly. More importantly, implementing a butterfly mesh in this example would have made it more complicated than appropriate for a beginner's tutorial.

Everywhere except near where block corners are folded out to lie on the pipe, the mesh is quite good. The mesh is even better if the ends of the pipes are relaxed, and then solid regions are relaxed. For example, try these commands:

```
tmei 1 2;-1 0 -4;1 3; 30 0 1
tmei 1 2;1 4;1 3;30 0 1
```

The first **T**homas **M**iddlecoff **E**lliptic relaxation command smooths the two ends of the elbow pipe. The second smooths the interior, using the walls of the pipe as boundary conditions. Each performs 30 iterations of the relaxation method. The `tmei` command is better than usual techniques of elliptic relaxation for problems where elements need to be nearly orthogonal to the boundary. Furthermore this type of smoothing tends to better respect zoning requirements than other elliptic relaxation

methods. Note that **True*Grid*®** also supports equi-potential relaxation (`relax`).

Part Replication

Most simulation codes deal nicely with planes of symmetry. Therefore, this half model is good enough in most cases. However, it is not problem to duplicate the current model, and glue the two sides together.

The **L**ocal **C**oordinate **T**ransformation command (**lct**) allows the user to specify transformations to apply to a model. Then the **L**ocal **RE**plication command (**lrep**) is used to create copies of the current part using the local coordinate transformations.

In this example, we create a "mirror image" part by reflecting the current part across the XY plane. Create a dialogue box for the `lct` command by pressing the **LCT** button in the **REPLICATION** submenu. Enter `1` for the "NUMBER OF TRANSFORMATIONS". Under the "LIST OF TRANSFORMATIONS", choose the reflection option

```
> Reflect about the x-y plane
```

End the current transformation, and the list of transformations by selecting

```
> End Transformation and List
```

Execute and Quit this dialogue box.

Issue the next command to replicate the current part.

```
lrep 0 1;
```

This command tells **True*Grid*®** to preserve the part as it is (transformation 0) and to replicate the part using the first defined local transformation.

As soon as the `endpart` command is issued, **True*Grid*®** creates the required copies of the current part. Combine this with the command to enter the Merge Phase

```
endpart merge
```

To complete the model, we need to eliminate the duplicate nodes along the symmetry plane. This is done using the **S**tandard **P**art **T**olerance command:

```
stp 0.01
```

This command causes **True*Grid*®** to merge all nodes that are within a distance of 0.01 of each other. Merging is fast, easy, and versatile. Furthermore, you can interactively change the merging by simply issuing new merging commands. (Look at the help package for the MERGING category of commands.)

The merged nodes are displayed using the **LABELS** dialogue in the **GRAPHICS** submenu. Choose the following option to display the merged nodes:

```
> Merged Parts
```

Writing the Mesh File

The final output file is written using the `write` command with no arguments. The default output file name is "trugrdo". The name can be specified on the command-line.

Some output options require selecting the type before creating the first part. Others can be selected at the end.

For more information about output options, look at the help package for the **OUTPUT** category of commands. Help for an individual output option gives a list of all supported boundary conditions, element types, materials, etc. The commands used to set such conditions are also specified.

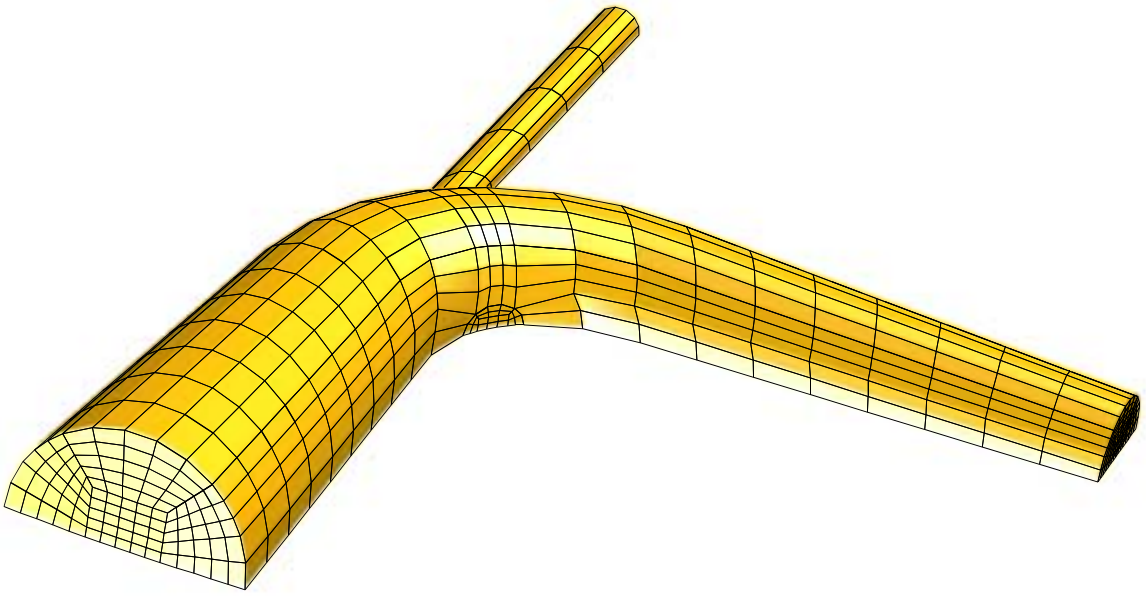
Boundary conditions are set in the Part Phase using the computational highlighting system to point to parts of the mesh. Boundary conditions cannot be specified later.

The Double Butterfly Version of the Mesh

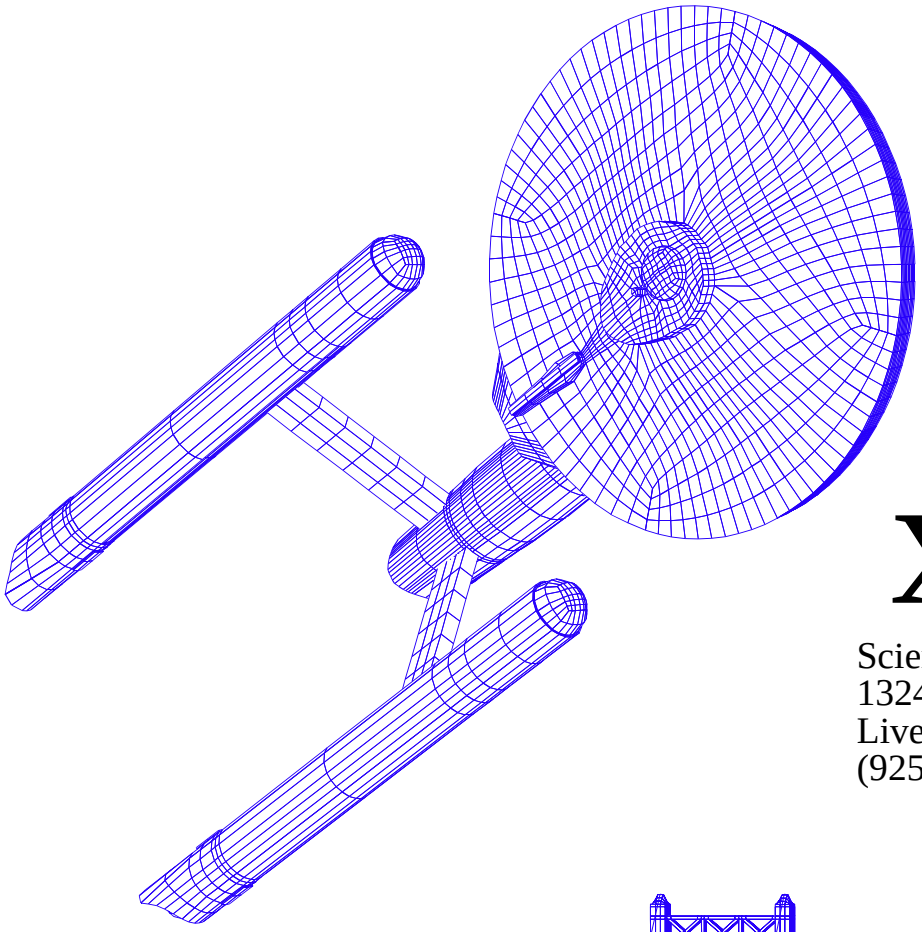
As promised earlier, a picture of a "double butterfly" version of the current example is shown.

Zoning has not yet been performed on the model shown. Nor has any relaxation been done. This picture demonstrates that a block-structured mesh of the intersecting pipe problem can be created which does not suffer from the side effect of putting a square peg into a round role.

This example file is called **dblbtrf**. Try a little zoning and relaxation on the model. Examine the block structure. It's an interesting example.



The Double Butterfly Mesh



XYZ

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