USER DOCUMENTATION

INTRA**LATTICE**

CORE MODULES

v0.7.5

PREFACE

VERSION **0.7.5** — ALPHA

INTRA**LATTICE** is a C# plugin for Grasshopper, used to generate solid lattice structures within a design space. It was developed as an extensible, open-source alternative to current commercial solutions. As an ongoing project developed at McGill's Additive Design & Manufacturing Laboratory (ADML), it has been a valuable research tool, serving as a platform for breakthroughs in multi-scale design and optimization.

By providing a modular approach to lattice design, and giving you full access to the source, we hope to collectively explore lattice design at a deeper level, and consequently, engineer better products.

WEBSITE — http://intralattice.com

SOURCE CODE — https://github.com/dnkrtz/intralattice/

DEVELOPER DOCS — http://intralattice.com/devdocs

THE MIT LICENSE

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SUPPORT

If you have any issues, questions or feedback — please contact support@intralattice.com

LEAD DEVELOPERS

This project was started in the summer of 2014. Although the process was a collaborative effort, the contributions can be broadly categorized as follows:

Aidan Kurtz — Development of CORE modules, website and documentation.

Yunlong Tang — Development of OPTI modules (PhD research).

Prof. Fiona Zhao — Project supervisor and head of the research lab.

ACKNOWLEDGEMENTS

Many students/researchers have contributed to the project since its inception.

Marc Wang —

Ken Nsiempba —

Huiyuan Yang —

If you submit a pull request to the GitHub repository, and it is merged, your name and contribution will be listed. For more information on how to contribute, refer to the Developer Documentation.

The mesh generation methods used in this project are based on the Exoskeleton algorithms developed by David Stasiuk. And of course a big thanks to David Rutten for his work on Grasshopper.

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0.0 BACKGROUND

The freedom of form enabled by 3D printing has allowed engineers to integrate new orders of complexity into their designs. The goal of this research was to develop **a set of CAD tools for generating solid lattice structures** within a design space. The software would be used to:

- Reduce volume/weight while maintaining structural integrity.
- Increase surface area as a means of maximizing heat transfer.
- Generate porosity in bone scaffolds and implants.
- Serve as a platform for topology optimization.

In doing so, it should always output a watertight mesh suited for 3D printing. The lack of flexibility of current software solutions was the motive for this project. We wanted to develop a flexible platform more conducive to research, which would allow us to explore and experiment with lattice design at a deeper level. The obvious first step was to decide in which environment we would develop our system. Rhinoceros is known to be very open ended, having its own engine for interpreting scripts (Python, C# and VB), and a powerful plugin SDK (RhinoCommon). Its Grasshopper addon is a visual programming tool widely used in architecture which provides an ideal interface for systematic design. In this visual interface, parameters and function components are combined sequentially to carry out the design of 3D models. By developing a set of custom components for Grasshopper, we could establish a modular workflow for generative lattice design.

That being said, if you are not familiar with Grasshopper, you are highly encouraged to have a look at the latest Grasshopper Primer, to bring you up to speed.

0.1 SYSTEM REQUIREMENTS

Operating System:	Windows 7 or 8 (64-bit recommended)
RAM:	8GB or more
Video Card:	OpenGL 2.0 capable video card
CPU:	No more than 63 CPU cores

0.2 INSTALLATION

The following **required software** should be installed on your system.

- **Rhinoceros 5**
- **Grasshopper**

Next, if you haven't yet, download the latest version of INTRA**LATTICE**

- **Intralattice**

To install, simply drag the 'IntraLattice.gha' file into your Grasshopper viewport. A new toolbar will appear.

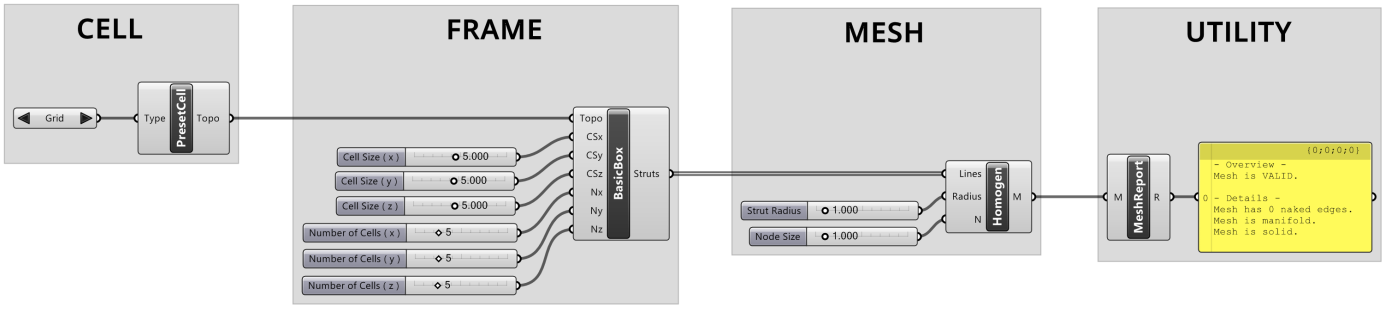
Section 1

CORE FRAMEWORK

As mentioned previously, INTRALATTICE is a set of components for Grasshopper, a visual scripting tool with an intuitive interface for creating algorithms that generate 3D models. This is particularly useful for designing cellular structures; a process that is parametric/systematic by nature. The core framework consists of all modules concerned with the modeling of lattice structures. This process is split into a set of modules, each carrying out a specific sub-process. The benefits of defining a modular workflow include:

- **Flexibility** : each module can be changed independently; several components are available.
- **Progressive computation** : you can preview each module before computing the next.

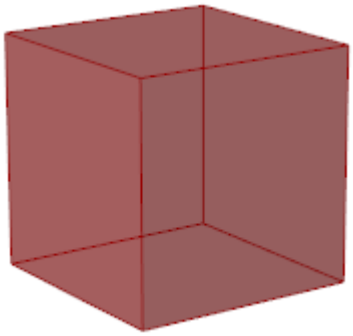
In Grasshopper, this modular approach looks like this.

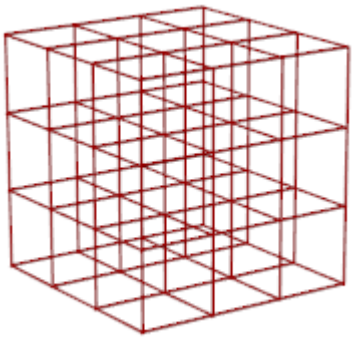


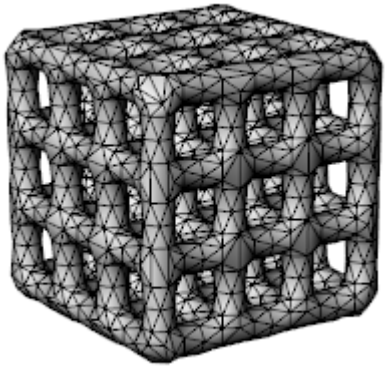
The **CELL** module generates the unit cell. The **FRAME** module takes in this unit cell, and various lattice parameters, and outputs a wireframe of the lattice, as a list of curves. The **MESH** module then takes in the list of curves and outputs a single solid mesh, which can be baked and saved in any standard format (i.e. STL, OBJ, PLY, etc…). The **UTILITY** module is optional, and includes a set of tools for pre/post-processing.

1.0 CORE MODULES

The core framework is shown below.







The core framework is shown below.

Section 2

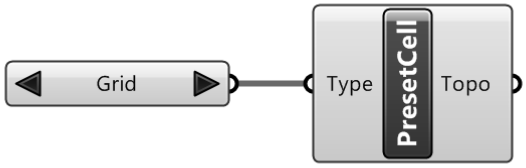
CELL MODULE

Intralattice generates cellular lattice structures, meaning the topology is based on a unit cell. For the time being, our approach uses cubic unit cells, but we hope to extend capabilities to include tetrahedral cells.

Generates the unit cell, as a list of lines. The **PresetCell** component provides a selection of built-in unit cells. Users may also define custom unit cells with the **CustomCell** component. This custom design can be imported from any CAD software, or defined directly in Grasshopper.

2.0 PRESET CELL

Description — Built-in selection of unit cell topologies.



INPUTS

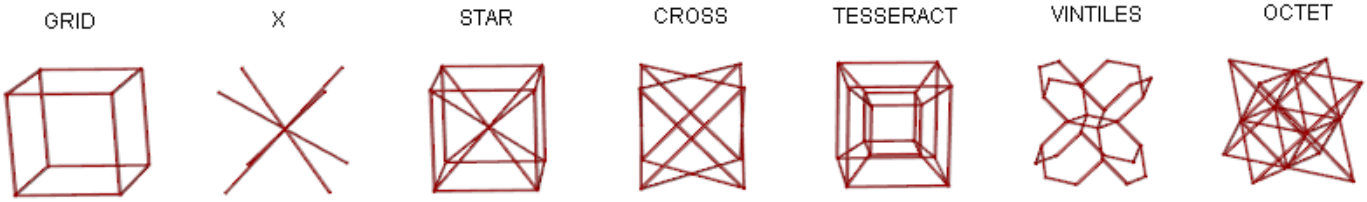
Type Integer representing the unit cell topology selection.

OUTPUTS

Topo Cell topology as a UnitCell object (custom data type).

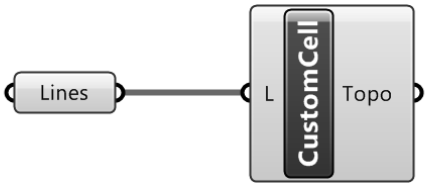
EXAMPLES

This example shows some of the built-in unit cell topologies.



2.1 CUSTOM CELL

Description — This component can be used to pre-process a custom unit cell. It will verify that the cell is valid, and return an error if it fails any of the validity tests.



INPUTS

L	List of curves representing your unit cell. (*note:* must be linear curves)

OUTPUTS

Topo	Cell topology as a UnitCell object (custom data type).

2.1.0 What is a valid unit cell?

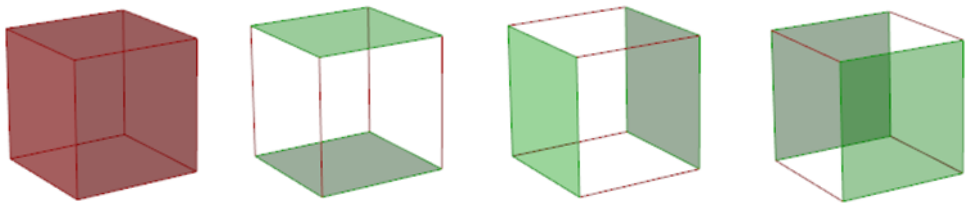
All unit cells generated by the PresetCell component are valid, and to that extent, the following information isn't useful. However, when designing custom unit cells, you need to keep in mind that the INTRALATTICE framework is built around a set of assumptions. The primordial assumption is that the cell has a cubic bounding box. Other requirements include:

Requirement 1 : All struts are linear.

The next two requirements are concerned with continuity within the lattice.

Requirement 2 : Each face of the bounding box of the cell has at least 1 node lying on it.

Requirement 3 : Opposing faces of the bounding box have the same nodes.



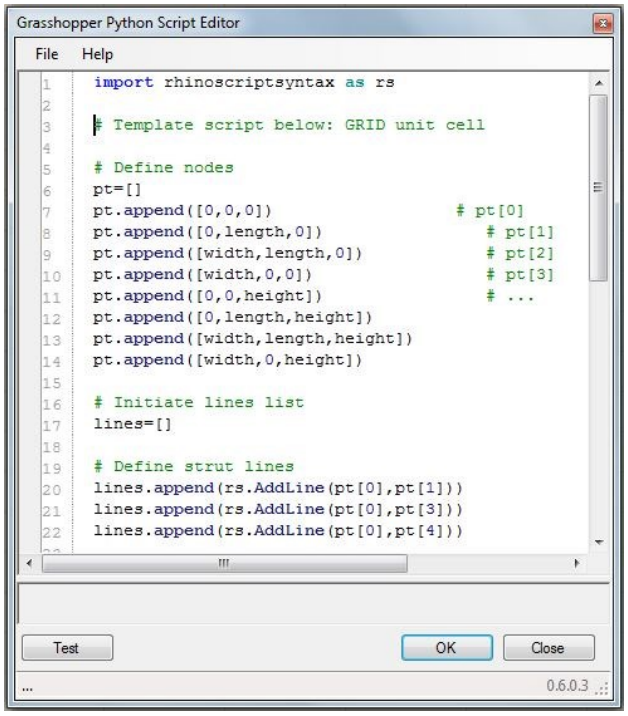
2.1.0 Import a custom unit cell from any CAD software

Once you've created a unit cell as a set of lines, save it in a universal format.

1) **Open the file** in Rhinoceros.
   A) In Rhinoceros, go to "File -> Open".
   B) Select your file.
2) **Set the curves** in Grasshopper.
   A) In Rhinoceros, select all lines that make up your unit cell.
   B) In Grasshopper, right-click on the 'L' input, then choose "Set multiple curves".
3) **Internalise the data** on the CustomCell component.
   A) In Grasshopper, right-click on the 'L' input, then choose "Internalise data".
   The unit cell geometry is now being stored inside Grasshopper.
4) **Remove curves** from Rhinoceros.
   A) In Rhino3D, select all the lines and click Delete.

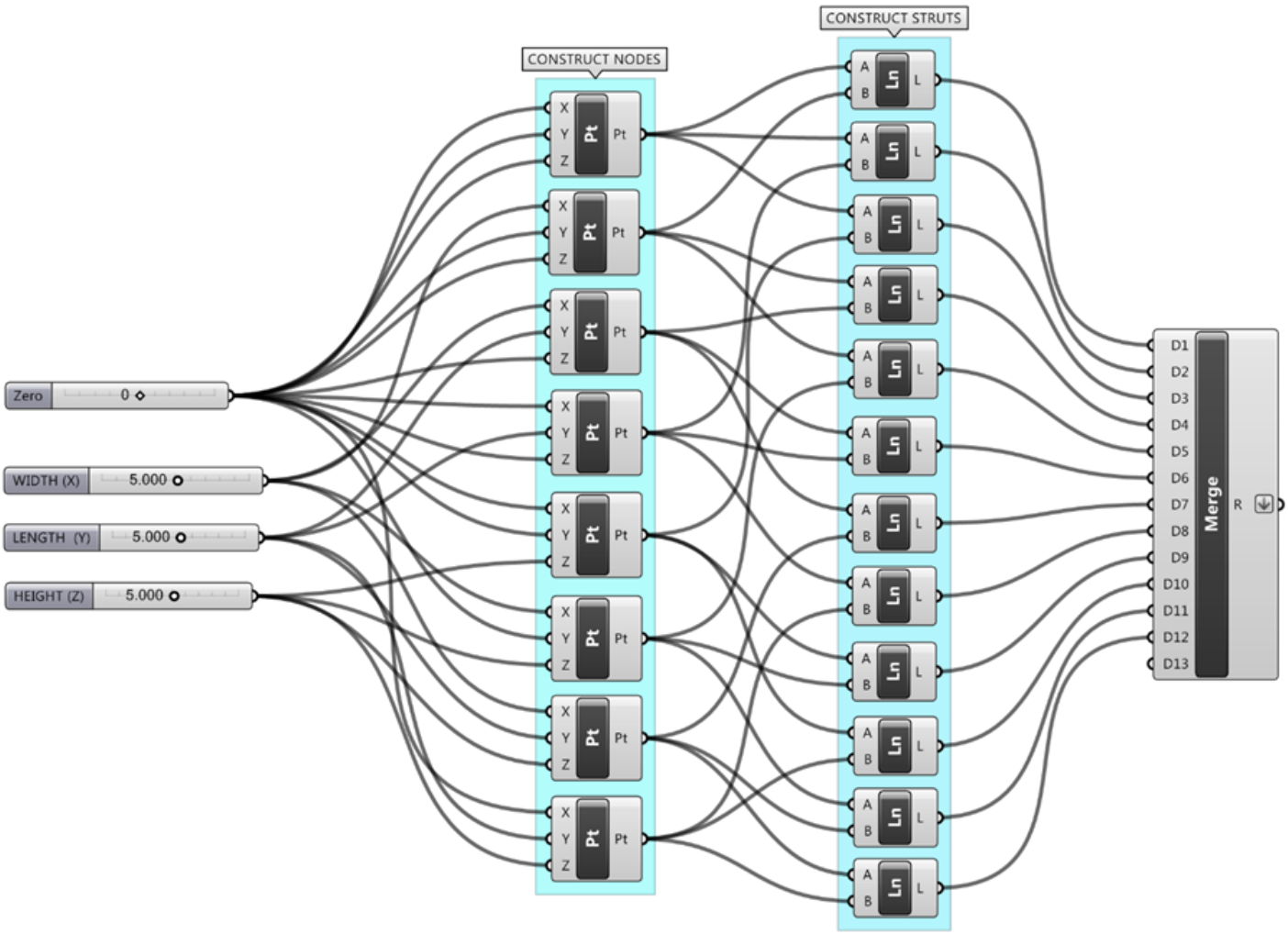
2.1.1 Create custom cell in C#/VB/Python script

Grasshopper has built-in scripting components for C# and VB. You may also extend the scripting capabilities to Python by downloading/installing [GhPython](). An example Python script is shown below:



2.1.1 Create custom cell in Grasshopper

Another efficient way of designing unit cells is directly in Grasshopper. The figure below shows a simple example of how this could be done for the simple grid topology.



Section 3

FRAME MODULE

The frame module generates a wireframe of the lattice structure, based on the unit cell generated by cell module, and a design space.

Generates the lattice wireframe, as a list of lines (and a data tree of the nodes). This wireframe is based on the unit cell and a design space. The **BasicBox** and **BasicCylinder** components generate lattices within a pre-defined design space; ideal for quickly testing new cell topologies, and 3D printing samples for testing. The **ConformSS**, **ConformSA** and **ConformSP** components generate lattices that conforms to a surface-based design space. The **UniformDS** component generates a trimmed uniform lattice within a mesh or brep design space.

Note that our lattice structures generated are cellular structures by design, however, when pseudo-randomization is introduced, the cell boundaries dissolve (more on this later).

3.0 HOW TO DEFINE YOUR DESIGN SPACE

The first step to populating a design space with lattice, is figuring out how to define the space itself. There is a variety of ways of doing this, depending on the type of lattice you want to generate.

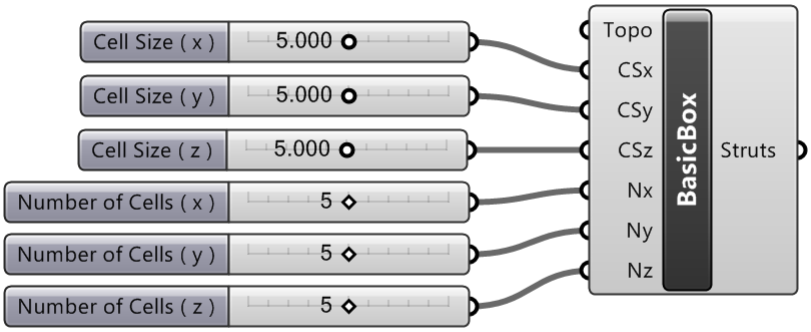
For Conform components, surface(s) define the design space. The UV-map of the surface is very important, and the Adjust UV component can be used to fix inconcistencies.

Command — ShrinkTrimmedSrf

Command — Explode

3.1 BASIC BOX

Description — Generates a lattice box.



INPUTS

Topo Topology data, output by cell module.

CSx, CSy, CSz Size of unit cells in each of the xyz Cartesian coordinates .

Nx, Ny, Nz Number of unit cells in each of the xyz Cartesian coordinates.

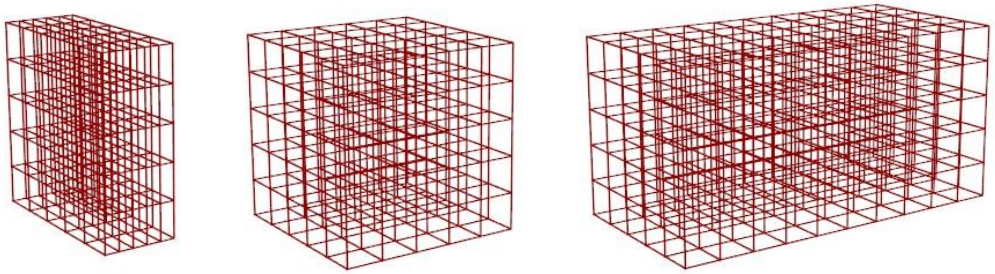
OUTPUTS

Struts List of curves representing the lattice struts.

EXAMPLES

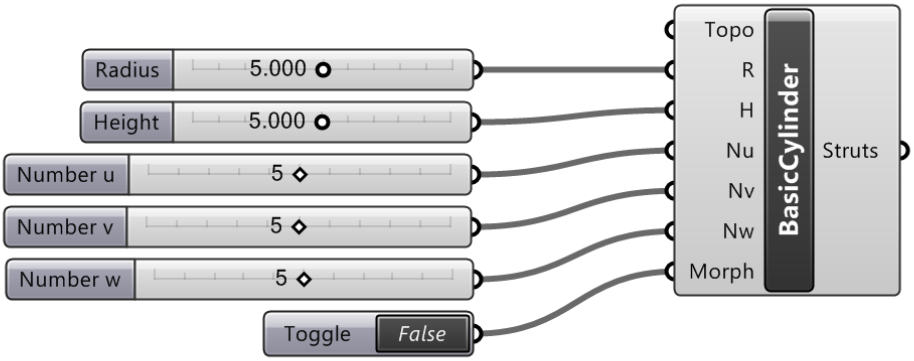
At this point, everything is pretty straight-forward. You can play with the size of unit cells, and also the number of cells in each direction.

Note that **all examples in this documentation will use the grid unit cell topology**, for clarity.



3.2 BASIC CYLINDER

Description — Generates a uvw-conforming lattice cylinder.



INPUTS

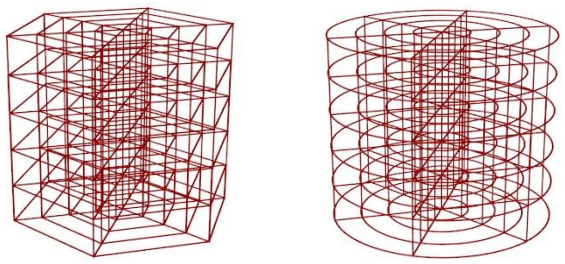
Topo	Topology data, output by cell module.
R, H	Cylinder radius and height, respectively.
Nu, Nv, Nw	Number of unit cells in each of the UVW-map coordinates. (u—axial, v—theta, w—radial)
Morph	Strut morphing. (if true, struts are morphed into curves)

OUTPUTS

Struts	List of curves representing the lattice struts.

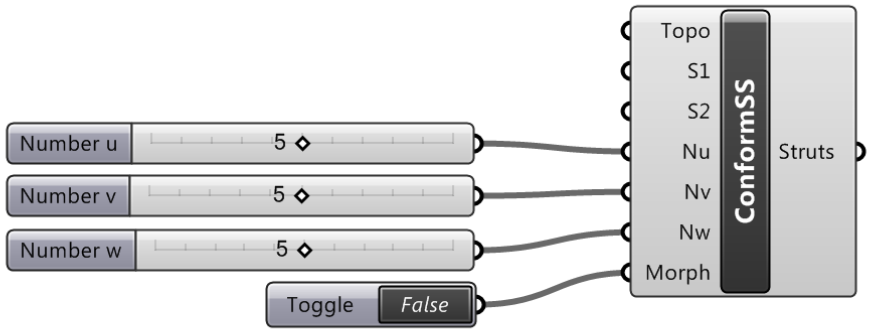
EXAMPLE

The example shown here illustrates **the effect of morphing**. While the nodes conform to the design space whether the structure is morphed or not, struts will not necessarily conform like we want them to. Using the Space morphing method discretizes the struts and maps an interpolated curve to the uvw-map.



3.2 CONFORM SURFACE-SURFACE

Description — Generates a uvw-conforming lattice between two surfaces.



INPUTS

Topo	Topology data, output by cell module.
S1, S2	The surfaces that define the design space. In some cases, you may need to pass one of the surfaces through the 'AjustUV' component to fix UV alignment issues.
Nu, Nv, Nw	Number of unit cells in each of the UVW-map coordinates.
Morph	Strut morphing. (if true, struts are morphed into curves)

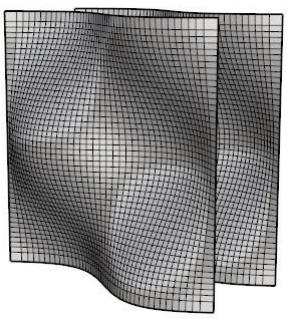
OUTPUTS

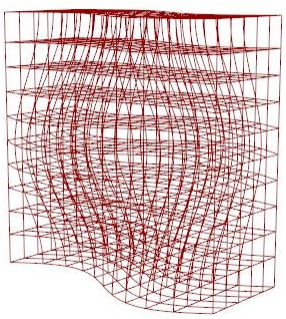
Struts	List of curves representing the lattice struts.

EXAMPLE

The example shows a pair of identical sinusoidal surfaces, and the space between them is filled with lattice. Of course, your surfaces do not need to be identical.

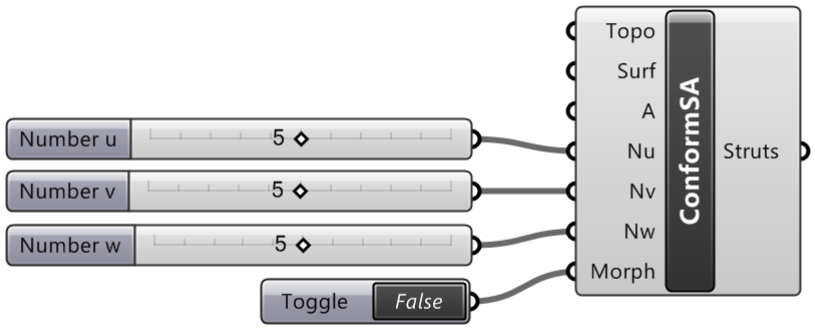
The lattice is conformed to the surfaces with the help of their UV maps, which are merged into a single UVW-map. You may input open or closed surfaces, such as spheres.





3.3 CONFORM SURFACE-AXIS

Description — Generates a uvw-conforming lattice between a surface and an axis.



INPUTS

Topo	Topology data, output by cell module.
S1, A	The surface and axis that define the design space, respectively. In some cases, you may need to pass one of the surfaces through the 'AjustUV' component to fix UV alignment issues.
Nu, Nv, Nw	Number of unit cells in each of the UVW-map coordinates. (u—axial, v—theta, w—radial)
Morph	Strut morphing. (if true, struts are morphed into curves)

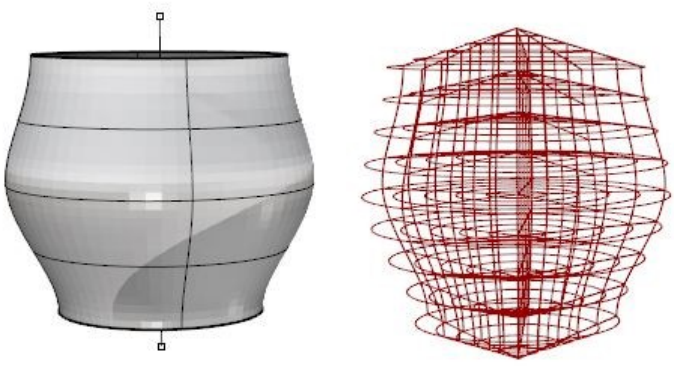
OUTPUTS

Struts	List of curves representing the lattice struts.

EXAMPLE

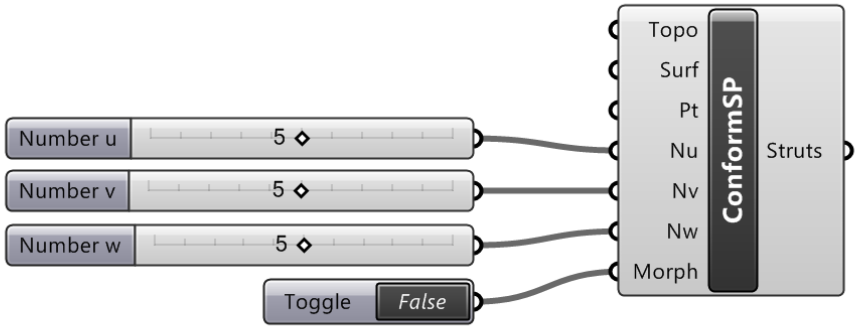
The lattice is conformed to the space between the axis and the surface by using the UV-map on the surface, and letting the axis be a U-map. The axis can be an open or closed curve. The surface can also be open or closed.

This example shows lattice being mapped to the space between a cylindrical surface and a linear axis which is slightly longer than the surface.



3.4 CONFORM SURFACE-POINT

Description — Generates a uvw-conforming lattice between a surface and a point.



INPUTS

Topo	Topology data, output by cell module.
S1, Pt	The surface and point that define the design space, respectively.
Nu, Nv, Nw	Number of unit cells in each of the UVW-map coordinates.
Morph	Strut morphing. (if true, struts are morphed into curves)

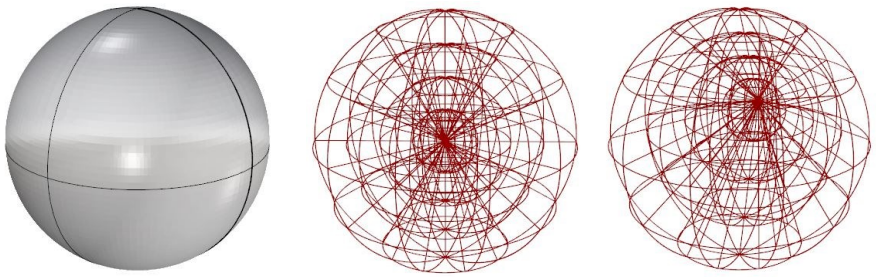
OUTPUTS

Struts	List of curves representing the lattice struts.

EXAMPLE

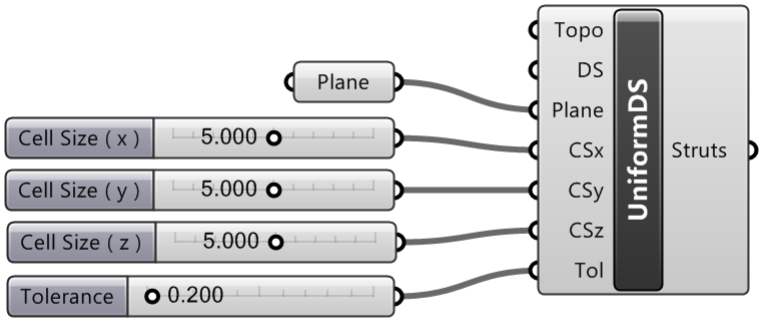
The lattice is conformed to the space between the axis and the surface by using the UV-map on the surface, and letting the axis be a U-map. The axis can be an open or closed curve. The surface can also be open or closed.

This example shows lattice being mapped to the space between a cylindrical surface and a linear axis which is slightly longer



3.5 UNIFORM DESIGN SPACE

Description — Generates a uniform lattice trimmed to the shape of the design space.



INPUTS

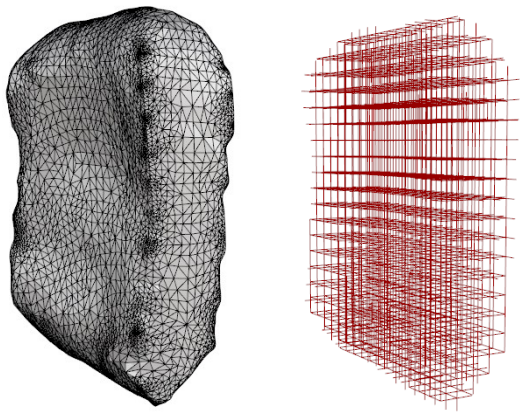
Topo	Topology data, output by cell module.
DS	The design space, as a Brep or a Mesh.
Plane	Orientation plane of the uniform lattice. (3 degrees of freedom)
CSx, CSy, CSz	Number of unit cells in each of the plane coordinate directions.
Tol	Minimum strut length. (trimming can result in very small struts)

OUTPUTS

Struts	List of curves representing the lattice struts.

EXAMPLE

The example here shows a craniofacial bone mesh, extracted from a CT scan. The design space is populated with a uniform lattice. Orientation of the lattice can be optimized using the Plane input. The design space may also be a Brep.



UNRESOLVED ISSUE

Meshes with many coplanar faces are **error prone**. Rhinoceros has trouble determining if a point is inside or outside the mesh in these cases.

Section 4

MESH MODULE

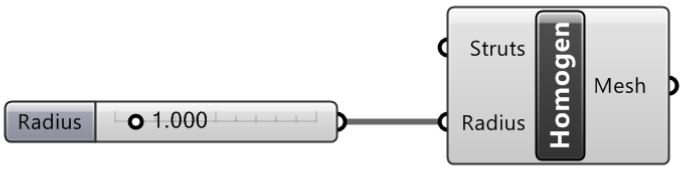
Generates solid mesh based on the lattice wireframe. The **Homogen** component generates a homogeneous mesh, meaning the strut radius is constant throughout the entire structure. The **HeterogenGradient** component generates a heterogeneous mesh, based on a set of predefined thickness gradients, but also lets the user define custom gradients mathematically. The **HeterogenCustom** component is used when the user wants to completely customize the thickness distribution.

The underlying mesh generation methods are based on Exoskeleton by David Stasiuk.

Note that these components currently lack robustness. If the

4.0 HOMOGENEOUS

Description — Generates a homogeneous mesh of the lattice. (constant strut radius)



INPUTS

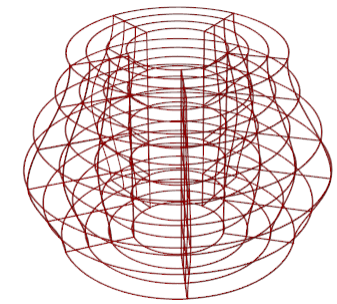
Struts List of curves representing the lattice struts.

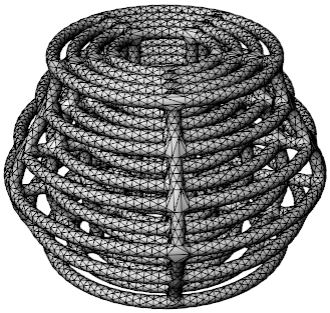
Radius Radius of the struts. Note that the actual thickness of the struts is double this value.

OUTPUTS

Mesh Solid mesh of the lattice.

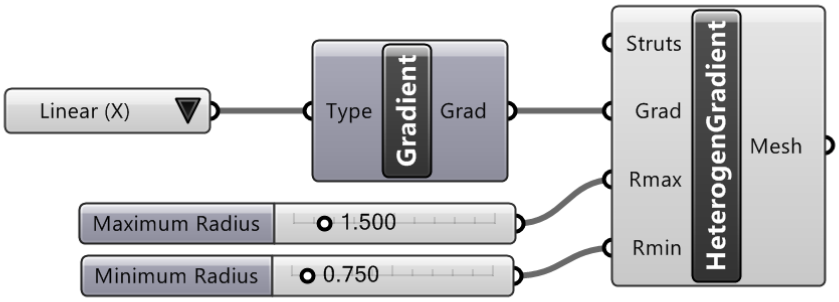
EXAMPLE





4.1 HETEROGENEOUS GRADIENT

Description — Generates a heterogeneous mesh of the lattice. (gradient strut radius)



INPUTS

Struts List of curves representing the lattice struts.

Grad Mathematical expression (string) representing a spatial gradient.

Rmax, Rmin Maximum and minimum strut radius.

OUTPUTS

Mesh Solid mesh of the lattice.

GRADIENT FUNCTION

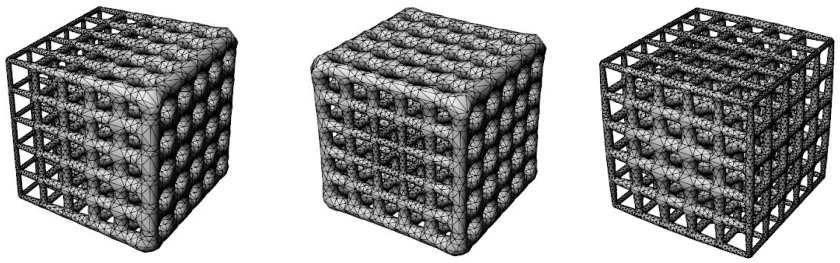
The spatial gradient (Grad) is a mathematical function g(x,y,z) with a unitized domain

0 < **x** < 1
0 < **y** < 1
0 < **z** < 1
0 < **g(x,y,z)** < 1

The radius of the struts at each node is proportional to value g(x,y,z), such that

g(x,y,z) = 0 → Radius = Rmin
g(x,y,z) = 1 → Radius = Rmax

EXAMPLE



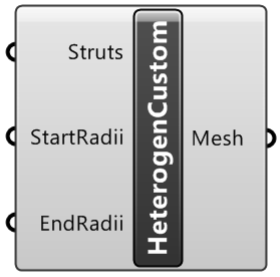
Linear gradient
g(x,y,z) = x

Cylindrical gradient
g(x,y,z) = Sqrt(Abs(2*x-1)^2 + Abs(2*z-1)^2)/Sqrt(2)

You can reverse the gradient by swapping Rmin and Rmax.
The PresetGradient component includes a library of gradient functions.
Of course, you may also define your own gradient functions.

4.2 HETEROGENEOUS CUSTOM

Description — Generates a heterogeneous lattice. (custom strut radii)



INPUTS

Struts	List of curves representing the lattice struts.
StartRadii	List of radii at the start of each strut, parallel to the Struts list.
EndRadii	List of radii at the end of each strut, parallel to the Struts list.

OUTPUTS

Mesh	Solid mesh of the lattice.

EXAMPLE

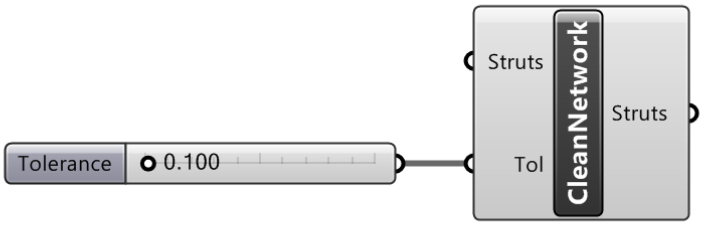
Section 5

UTILITY MODULE

Post-processing tools. The **MeshReport** component gives a comprehensive report of a mesh.
More coming soon...

5.0 CLEAN NETWORK

Description — Removes duplicate curves from a network, within specified tolerance.



INPUTS

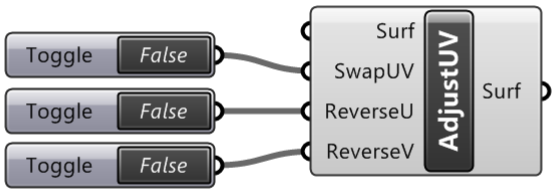
Struts	List of curves to be cleaned.
Tol	Tolerance for combining nodes.

OUTPUTS

Struts	Cleaned list of curves.

5.0 UV ADJUST

Description — Adjusts the UV-map of a surface for proper alignment with other surfaces/axes.



INPUTS

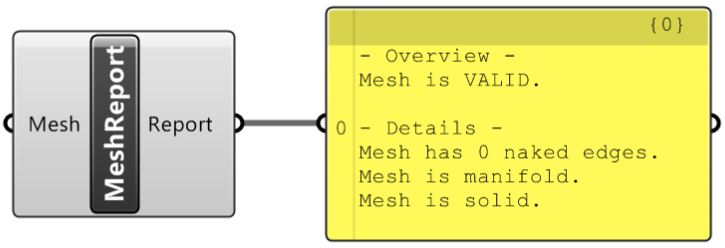
Surf	Surface to adjust.
SwapUV	Swap the uv parameters.
ReverseU	Reverse the u-parameter direction.
ReverseV	Reverse the v-parameter direction.

OUTPUTS

Surf	Adjusted surface.

5.0 MESH REPORT

Description — Verifies that the mesh represents a solid, and returns a comprehensive report.



INPUTS

Mesh The mesh to inspect.

OUTPUTS

Report Validity report, which refers to 3D printability.

5.0 MESH PREVIEW

Description — Verifies that the mesh represents a solid, and returns a comprehensive report.

INPUTS

Mesh The mesh to inspect.

OUTPUTS

A colored mesh and it’s edges are visible in the Rhinoceros viewport.

Section 6

CASE STUDIES

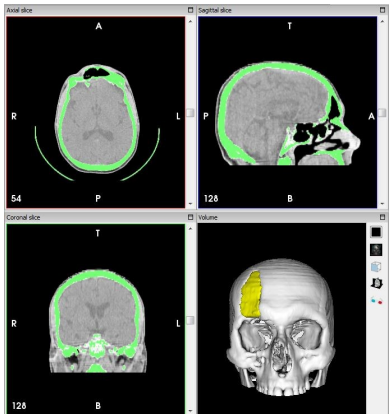
6.0 BONE GRAFTS

Bone tissue, unlike most other tissues, has the ability to regenerate when provided a space in which to grow. Bone grafting is a surgical procedure which aims to implant scaffold materials for reparative bone growth. The success of a bone graft relies on three biologic mechanisms: osteoconduction, osteoinduction and osteogenesis. Osteoconduction occurs when the graft serves as a scaffold upon which bone cells spread and form new bone. Naturally, the structural properties of this scaffold play an important role in this process.
Through the use of lattice structures, INTRA**LATTICE** allows us to manipulate the porosity and strength of the implant at various levels. First and foremost, defining the design space requires some form of medical imaging of the patient's fracture. Below, we will walkthrough the design process of a craniofacial bone graft implant.

I. CT Segmentation (using InVesalius software)

Based on a CT scan of the patients fractured skull, InVesalius reconstructed the set of medical images into a 3D representation. Then, by manually selecting voxels where cranial bone was missing, an implant space was defined (seen in yellow) and exported as a mesh (.stl).

For the record, this process was quite tedious and a more efficient approach is needed.



II. INTRA**LATTICE** Design Phase

The next step was to open the implant mesh in Rhino3D and select it as the design space in our Grasshopper algorithm. From here, experimenting with various lattice topologies and cell sizes allows us to manipulate the porosity and strength of the implant. In the example below, a grid-uniform-homogeneous lattice is generated:

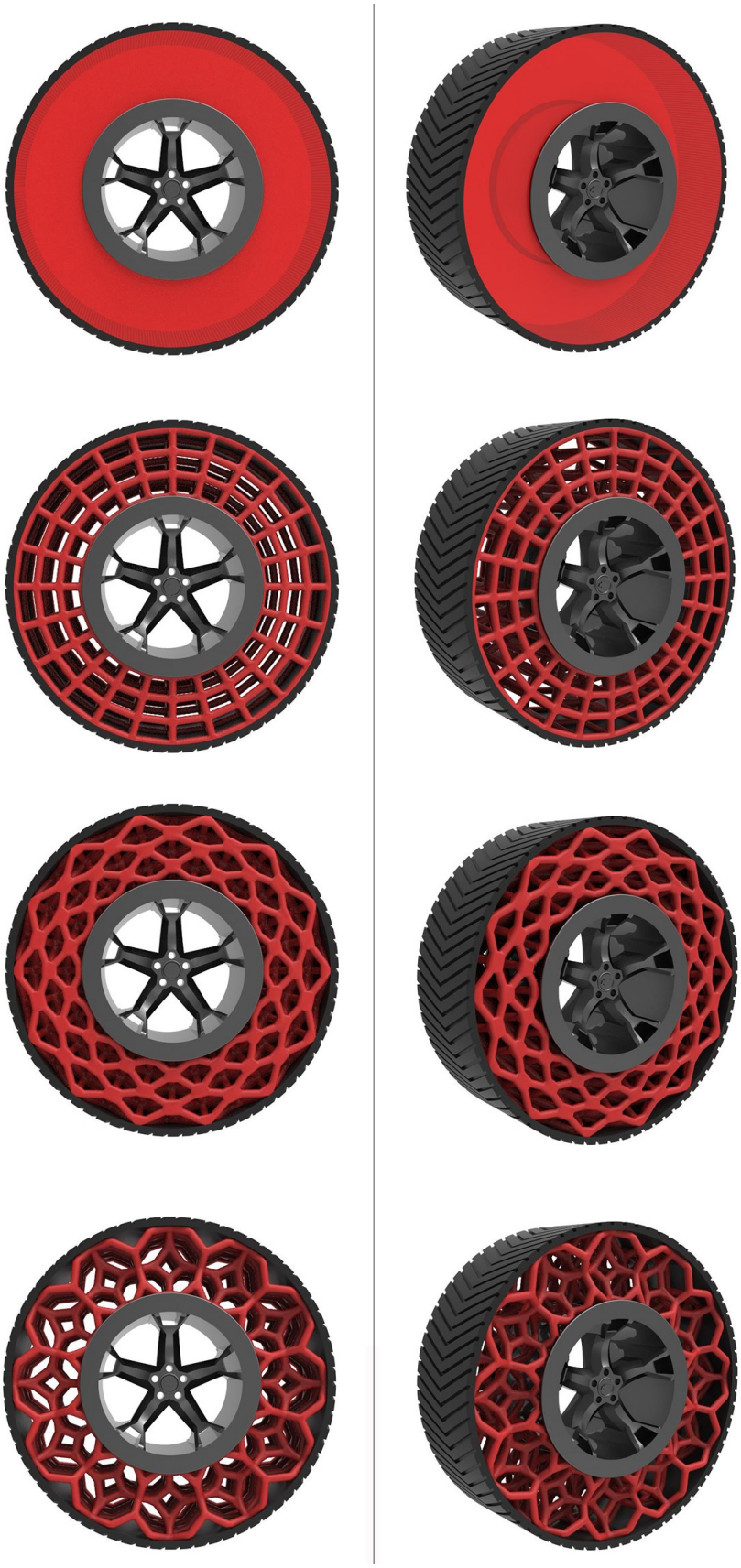
I Fractured Skull → **II** Solid Implant → **III** Porous Implant

6.1 CELLULAR TIRE

Airless tires are of particular interest in offroad, military and extra-terrestrial vehicles. In general, the quality of such tires is largely based on resilience. However, since this property is hard to evaluate through FEA, extensive physical testing is required to validate the quality of a design. In this case study, we simply show prototypes which would be tested, the quality of these designs is unknown.

As usual, the first step was to define a design space, which in this case, was the space between the tire thread and the wheel rim.

Next, we set the various design parameters, such as unit cell type, conformal iteration values and strut radius, and the lattice is generated.

By changing the design parameters, we easily obtain very diverse structures. In the figure shown here, you can see, in order of appearance:

1. Bare design space
2. Grid conformal lattice
3. Octet conformal lattice
4. Vintiles conformal lattice