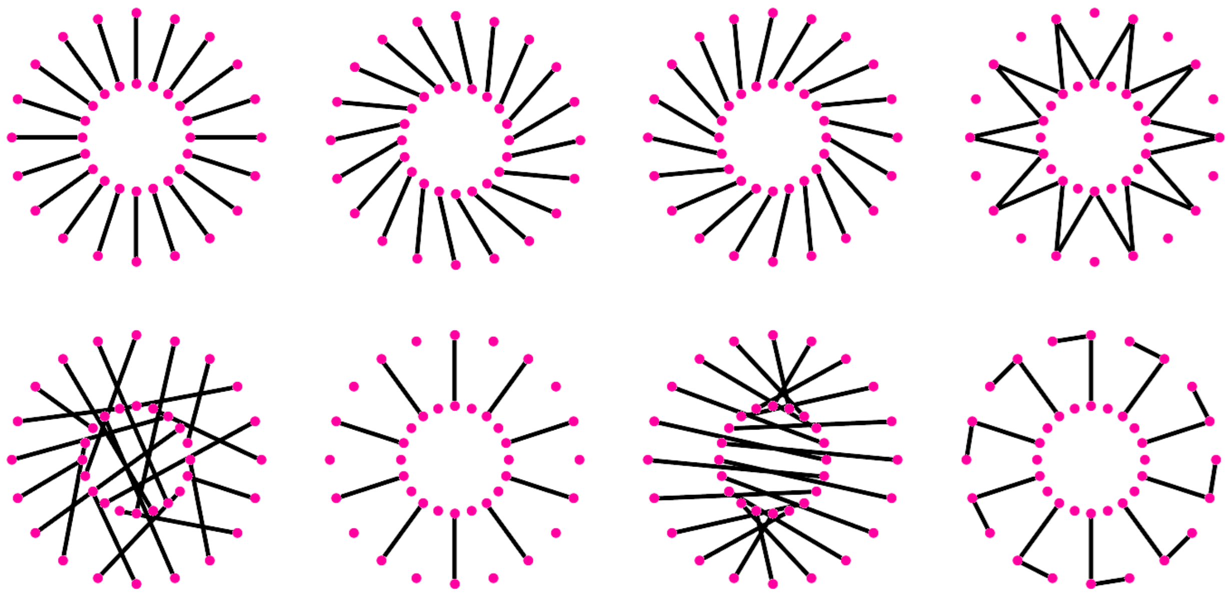

Essential Algorithms and Data Structures

for Computational Design in Grasshopper

Second Edition

Rajaa Issa

Robert McNeel & Associates

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Preface

The **Essential Algorithms and Data Structures for Computational Design** introduces effective methodologies to develop complex 3D modeling algorithms using Grasshopper. It also covers extensively the data structure adopted by Grasshopper and its core organization and management tools.

The material is directed towards designers who are interested in parametric design and have little or no background in programming. All concepts are explained visually using Grasshopper® (GH), the generative modeling environment for Rhinoceros® (Rhino). This book is not intended as a beginners guide to Grasshopper in terms of user interface or tools. Basic knowledge of the interface and workflow is assumed. For more resources and getting started guides, go to the *learn* section in www.rhino3d.com.

The content is divided into three chapters. Chapter 1 discusses algorithms and data. It introduces a rigorous methodology to help create and manage parametric solutions. It also introduces basic data concepts such as data types, sources and common ways to process them. Chapter 2 reviews basic data structures in Grasshopper. That includes single items and lists. Chapter 3 includes an in-depth review of the tree data structure in Grasshopper and practical applications in design problems. All Grasshopper examples and tutorials are written with Rhinoceros version 6 and are included in the download.

Rajaa Issa

Robert McNeel & Associates

Chapter One: Algorithms and Data

Algorithms and data are the two essential parts of any parametric design solution, but writing algorithms is not trivial and requires a skill that does not come easy to intuitive designers. The algorithmic design process is highly logical and requires explicit statements of the design intention and the steps to achieve them. This chapter introduces a methodology to help creative designers develop new algorithmic solutions. All algorithms involve manipulating data and hence Algorithms and Data are tightly connected. We will introduce the basic concepts of data types and processes.

1_1: Algorithmic design

We can define algorithmic design as a design method where the **output** is achieved through **well-defined steps**. In that sense, many human activities are algorithmic. Take, for example, baking a cake. You get the **cake** (output) by using a **recipe** (well-defined steps). Any change in the **ingredients** (input) or the baking process results in a different cake. We will analyze the parts of typical algorithms, and identify a strategy to build algorithmic solutions from scratch.

Regardless of its complexity, all algorithmic solutions have 3 building blocks: **input**, **key process**, and **output**. Note that the key process may require additional input and processes.

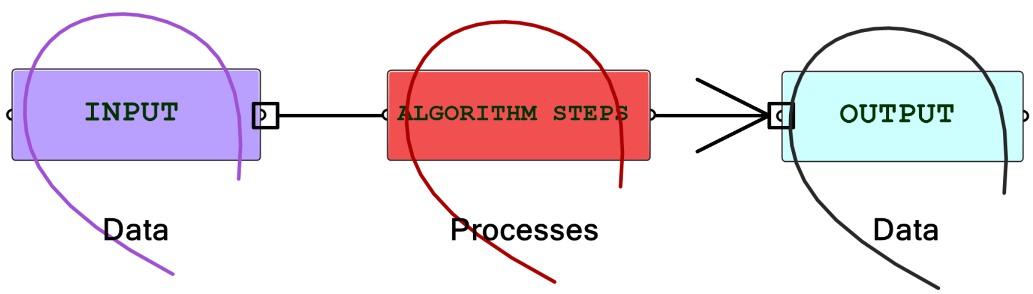


Figure (1): The building blocks of algorithmic solutions

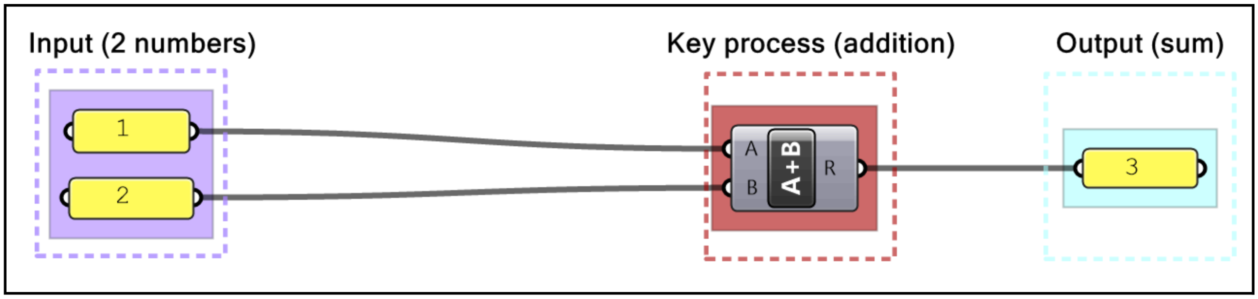
Throughout this text, we will organize and label the solutions to identify the three blocks clearly. We will also use consistent color coding to visually distinguish between the parts. This will help us become more comfortable with reading algorithms and quickly identify input, key processing steps, and properly collect and display output. Visual cues are important to develop fluency in algorithmic thinking.

In general, reading existing algorithmic solutions is relatively easy, but building new ones from scratch is much harder and requires a new set of skills. While it is useful to know how to read and modify existing solutions, it is essential to develop algorithmic design skills to build new solutions from scratch.

1_2: Algorithms parts

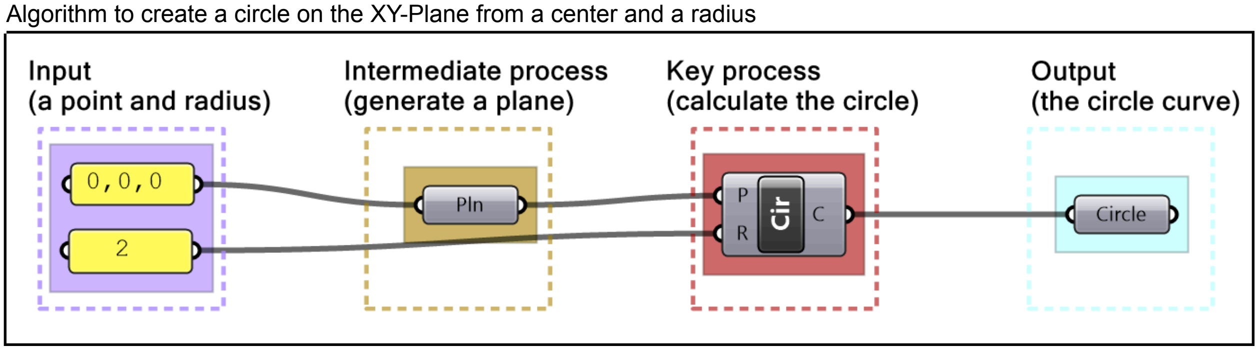
In Grasshopper, a solution flows from left to right. At the far left are input values and parameters, and the far right has the output. In between are one or more key processes, and sometimes additional input and output. Let's take a simple example to help identify the three parts of any algorithm (input, key process, output). The simple addition algorithm includes two numbers (input), the sum (output) and one key process that takes the numbers and gives the result. We will use purple for the input, maroon for the key processes and light blue for the output. We will also group and label the different parts and adhere to organizing the Grasshopper solutions from left to right.

Example 1-2-1:
Algorithm to add 2 numbers



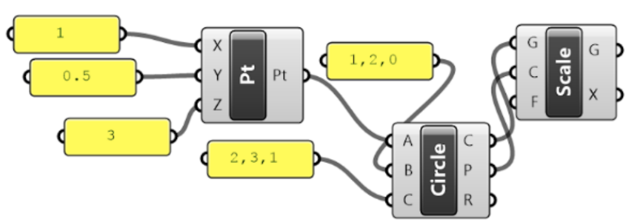
Algorithms may involve intermediate processes. For example, suppose we need to create a circle (output) using a center and a radius (input). Notice that the input is not sufficient because we do not know the plane on which the circle should be created. In this case, we need to generate additional information, namely the plane of the circle. We will call this an intermediate process and use brown color to label it.

Example 1-2-2:
Algorithm to create a circle on the XY-Plane from a center and a radius



Some solutions are not written with styles and hence are hard to read and build on. It is very important that you take the time to organize and label your solutions to make them easier to understand, debug and use by others.

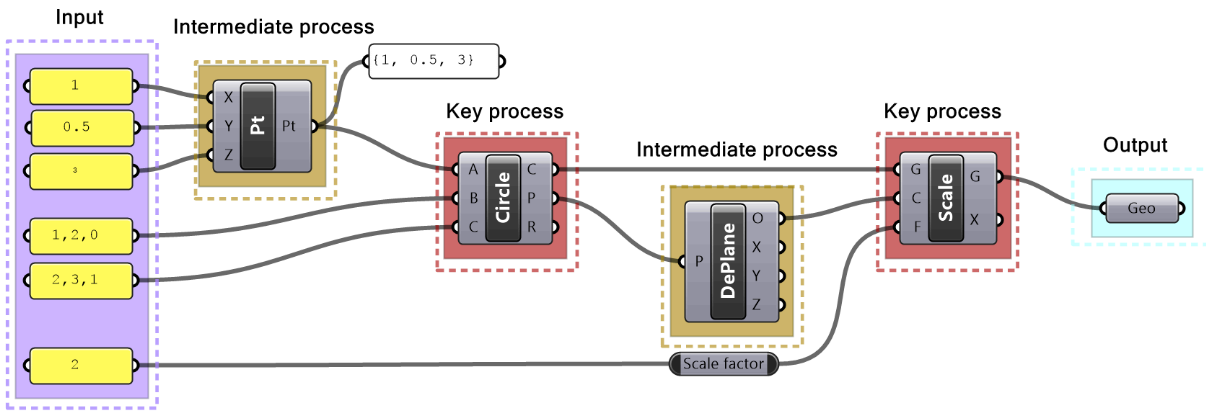
Tutorial 1-2-3: Read existing algorithm
Given the following definition, write a description of what the algorithm does, identify input, the main process(s) and output, then label and color-code all the parts. Re-write the solution to make it more readable.



Solution

In order to figure out what the algorithm is meant to do, we need to group the input on the left side, and collect the output on the right side, then organize the processes in the order of execution. We then step through the solution from left to right to deduce what it does. We can examine and preview the output in each step.

The example of the tutorial is meant to create a circle that is twice as large as another circle that goes through three given points. One of the points is constructed out of its 3 coordinates.



1_3: Designing algorithms: the 4-step process

Before we generalize a method to design algorithms, let's examine an algorithm we commonly use in real life such as baking a cake. If you already have a recipe for a cake, you simply get the recommended ingredients, mix them, pour in a pan, put in a preheated oven for a certain amount of time, then serve. If the recipe is well documented, then it is relatively straightforward to use. As you become more proficient in baking cakes, you may start to modify the recipe. Perhaps add new ingredients (chocolate or nuts) or use different tools (cupcake container).

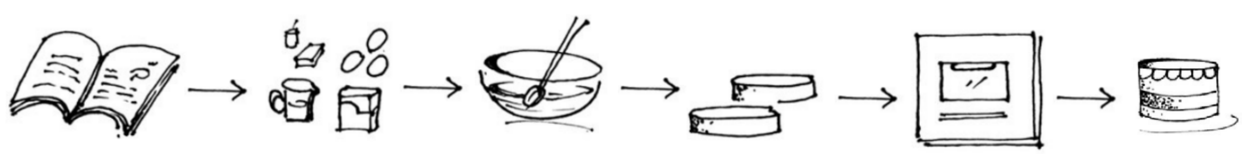


Figure (2): Steps to follow existing recipe

When designers write algorithms, they typically try to search for existing solutions and modify them to fit their purposes. While this is a good entry point, using existing solutions can be frustrating and time-consuming. Also, existing solutions have their own flavor and that may influence design decisions and limit creativity. If designers have unique problems, and they often do, they have no choice but to create new solutions from scratch; albeit a much harder endeavor.

Back to our example, the task of baking a cake is much harder if you don't have a recipe to follow and have not baked one before. You will have to guess the ingredients and the process. You will likely end up with bad results in the first few attempts, until you figure it out! In general, when you create a new recipe, you have to follow the process in reverse. You start with an image of the desired cake, you then guess the ingredients, tools and steps. Your thinking goes along the following lines:

- The cake needs to be baked, so I need an **oven** and **time**,
- What goes in the oven is a **cake batter** held by a **container,**
- The batter is a mix of **ingredients**

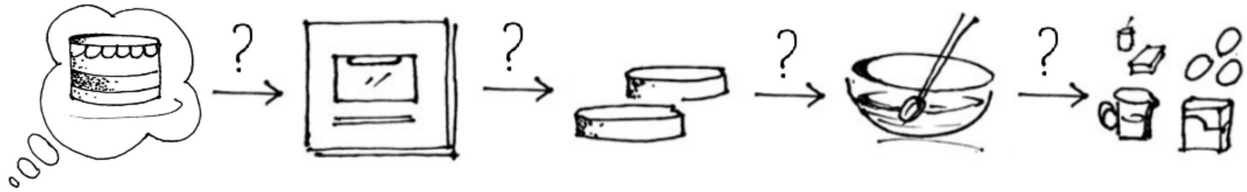


Figure (3): Steps to invent a new recipe from scratch

We can use a similar methodology to design parametric algorithms from scratch. Keep in mind that creating new algorithms is a “skill” and it requires patience, practice and time to develop.

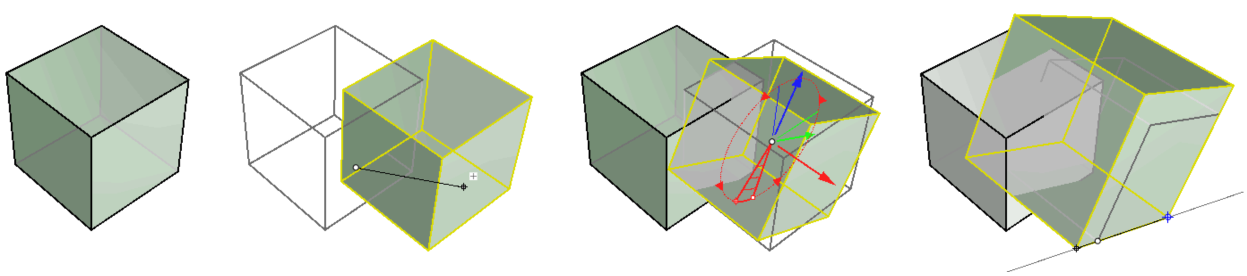
Algorithmic thinking in 3D modeling vs parametric design

3D modeling involves a certain level of algorithmic thinking, but it has many implicit steps and data. For example designing a mass model using a 3D modeler may involve the following steps:

1- Think about the output (e.g. a mass out of few intersecting boxes)
2- Identify a command or series of commands to achieve the output (e.g. run ***Box*** command a few times, ***Move***, ***Scale*** or ***Rotate*** one or more boxes, then ***BooleanUnion*** the geometry).

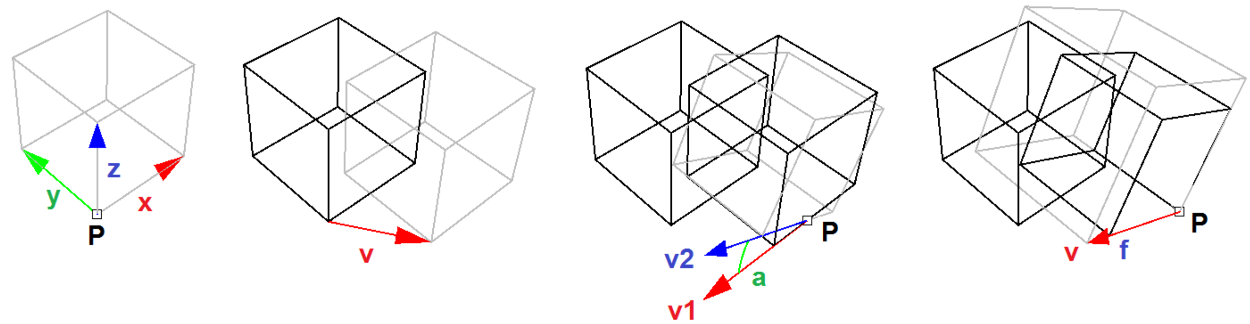
At that point, you are done!

Data such as the base point for your initial box, width, height, scale factor, move direction, rotation angle, etc. are requested by the commands, and the designer does not need to prepare ahead of time. Also, the final output (the boolean mass) becomes directly available and visible as an object in your document.



Figure(4): Interactive 3D modeling to create and manipulate geometry uses visual widgets and guides

Algorithmic solutions are not interactive and require explicit articulation of data and processes. In the box example, you need to define the box orientation and dimensions. When copying, you need a vector and when rotating you need to define the plane and angle of rotation.



Figure(5): Algorithmic solutions involve explicit definition of geometry, vectors and transformations

Designing algorithms

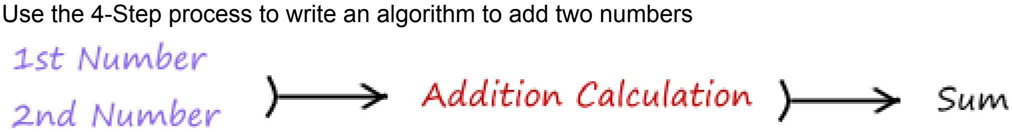
Designing algorithms requires knowledge in geometry, mathematics and programming. Knowledge in geometry and mathematics is covered in the ***Essential Mathematics for Computational Design***[1]. As for programming skills, it takes time and practice to build the ability to formulate design intentions into logical steps to process and manage geometric data. To help get started, it is useful to think of any algorithm as a 4-step process as in the following:

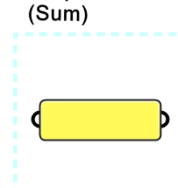
Output	1- Clearly identify the desired outcome
Key processes	2- Identify key steps to reach the outcome
Input	3- Examine initial data and parameters
Intermediate steps	4- Define intermediate parameters and processes to generate additional data

Thinking in terms of these 4 steps is key to developing the skill of algorithmic design. We will start with simple examples to illustrate the methodology, and gradually apply more complex examples.

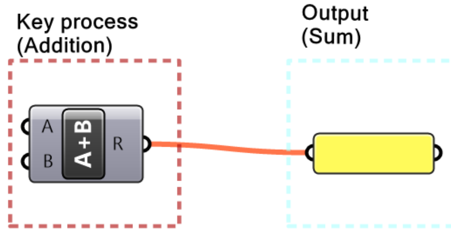
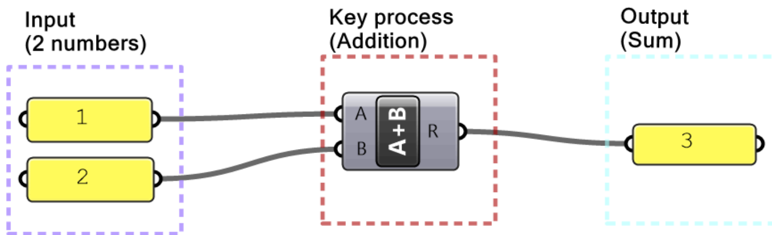
Example 1-3-1: Add two numbers

Use the 4-Step process to write an algorithm to add two numbers



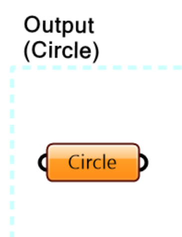
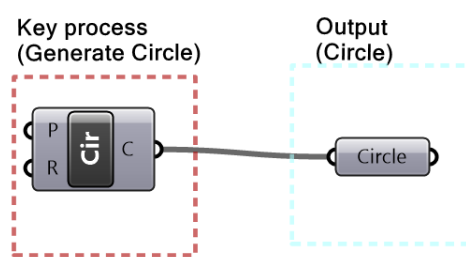
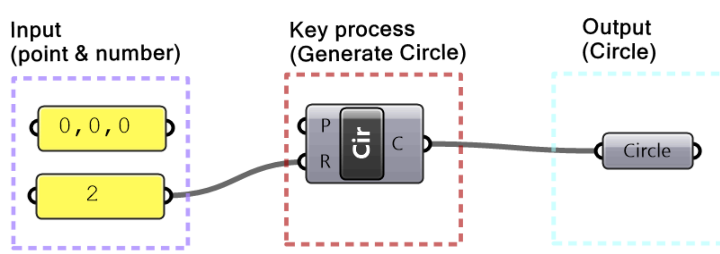
Step 1: Output: The sum of the 2 numbers Use a ***Panel*** to collect the sum	Output (Sum) 

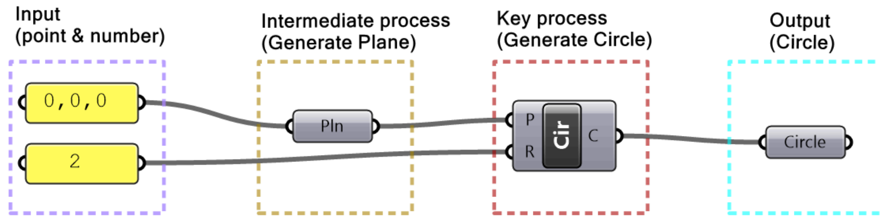
[1] Issa, Essential Mathematics for Computational Design, 4th edition, 2019. Free download of the PDF and examples: https://www.rhino3d.com/download/rhino/6/essentialmathematics

Step 2: Key process: Addition. Use the ***Addition*** component that takes 2 numbers and gives the sum	
Step 3: Input: 2 numbers. Use a ***Panel*** to hold and view the values of input numbers.	

Example 1-3-2: Create a circle

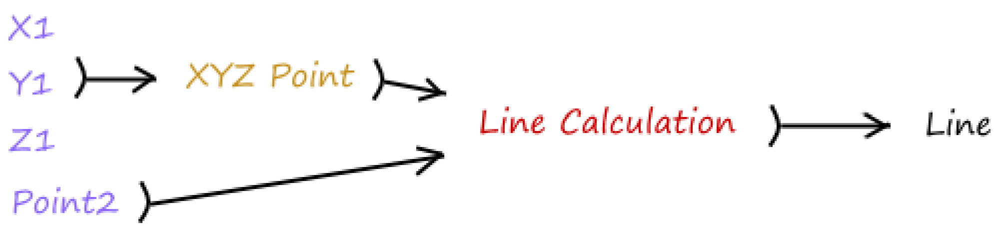
Use the 4-Step process to create a circle from a given center and radius

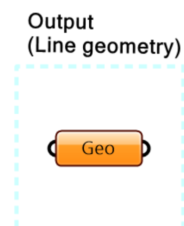
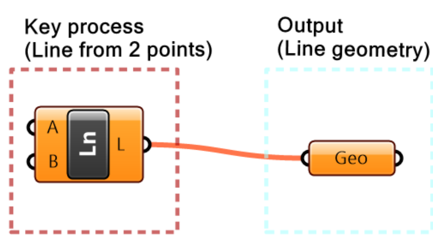
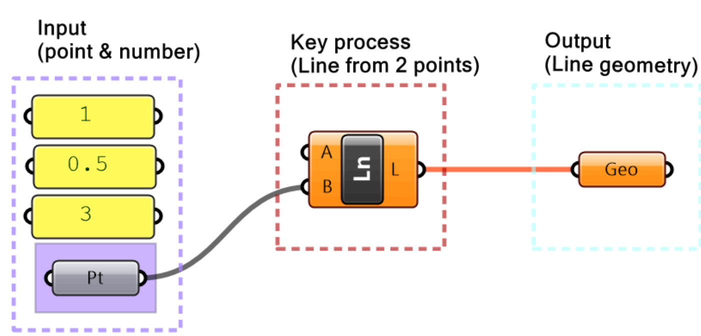
Step 1: Output: Circle. Use the ***Circle*** parameter to collect the output.	
Step 2: Key process: Identify a key process that generates a circle from a radius. Use the ***Circle*** component in Grasshopper.	
Step 3: Input: Use the given input (center and radius). Feed the radius to the ***Circle*** component.	

Step 4: Intermediate process: The circle needs a center, and also the plane on which the circle is located. Let's assume the circle is on a plane parallel to the XY-Plane and use the circle center as the origin of the plane.	

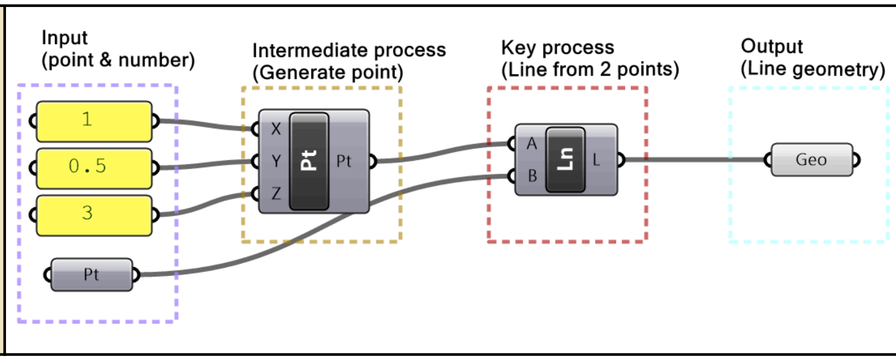
Example 1-3-3: Create a line

Use the 4-Step process to create an algorithm to generate a line from 2 points. One point is referenced from Rhino, and the other is created using three coordinates (x=1, y=0.5 and z=3).



Step 1: Output: The line geometry. Use the ***Geometry*** parameter to collect the output.	
Step 2: Key process: Identify a key process that generates a line from 2 points. Use the ***Line*** component in Grasshopper.	
Step 3: Input: Use the given input (a referenced point and 3 coordinates). Feed one point to one of the ends of the line.	

Step 4: Intermediate process:
Before we can use the coordinates as a point, we need to construct a point.



In more complex algorithms, we will need to analyze the problems, investigate possible solutions and break them down to pieces whenever possible to make it more manageable and readable. We will continue to use the 4-step process and other techniques to solve more complex algorithms throughout the book.

1_4: Data

Data is information stored in a computer and processed by a program. Data can be collected from different sources, it has many types and is stored in well defined structures so that it can be used efficiently. While there are commonalities when it comes to data across all scripting languages, there are also some differences. This book explores data and data structures specific to Grasshopper.

1_5: Data sources

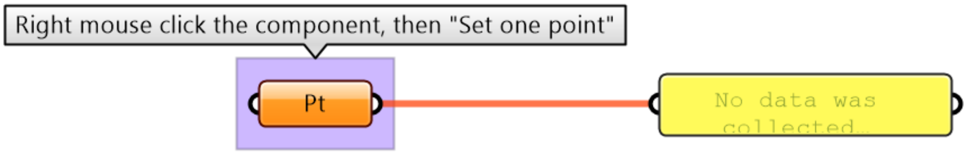
In Grasshopper, there are three main ways to supply data to processes (or what is called components): internal, referenced and external.

Data sources in Grasshopper

1- Internally set data
Data can be set inside any instance of a parameter. Once set, it remains constant, unless manually changed or overridden by external input. This is a good way when you do not generally need to change the data after it is set (constant). Data is stored inside the GH file.

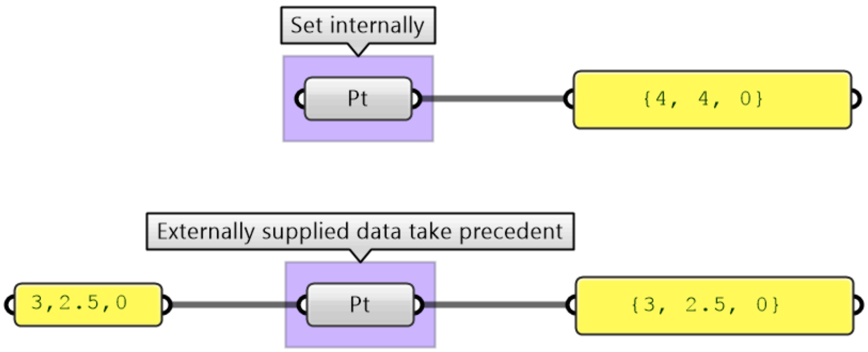
2- Referenced data
Data can be referenced from Rhino or some external document. For example, you can reference a point created in a Rhino document. When you move the point in Rhino, its reference in Grasshopper updates as well. Grasshopper files are saved separately from Rhino files, and hence if the GH file has referenced data, the Rhino file needs to be saved

and passed along with the GH file to avoid any loss of data.



3- Externally supplied data

Data can be supplied from previous processes. This method is best suited for dynamic data or data controlled parametrically. Externally supplied data to a parameter takes precedent over the internal or referenced values (when both exist).



1_6: Data types

All programming languages identify the kind of data used in terms of the values that can be assigned to and the operations and processes it can participate in. There are common data types such as ***Integer***, ***Number***, ***Text***, ***Boolean*** (Boolean type can be set to ***True*** or ***False***), and others. Grasshopper lists those under the ***Params > Primitives*** tab.

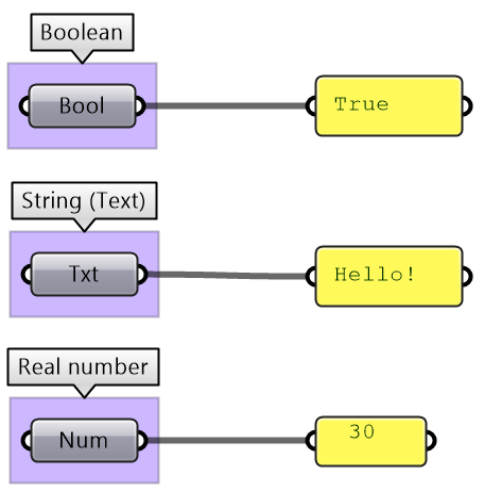


Figure (6): Examples of primitive data types common to all programming languages

Grasshopper supports geometry types that are useful in the context of 3D modeling such as ***Point*** (3 numbers for coordinates), ***Line*** (2 points), ***NURBS Curve***, ***NURBS Surface***, ***Brep***, and others. All geometry types are included under the ***Params> Geometry*** tab in GH.

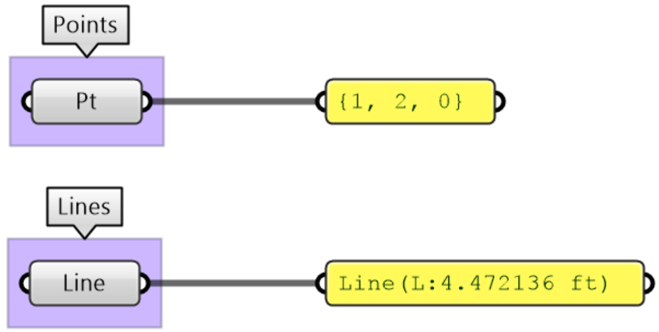


Figure (7): Examples of geometry data types

There are other mathematics types that designers do not usually use in 3D modeling, but are very common in parametric design such as ***Domains, Vectors, Planes,*** and ***Transformation Matrices***. GH provides a rich set of tools to help create, analyze and use these types. To fully understand the mathematical as well as geometry types such as NURBS curves and surfaces, you can refer to the ***Essential Mathematics for Computational Design*** book by the author.

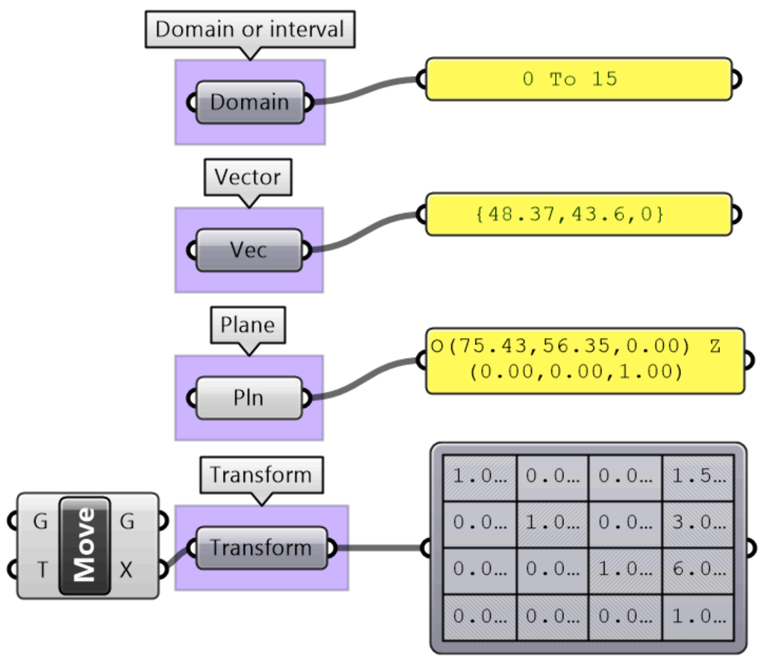


Figure (8): Examples of data types common in computer graphics

The parameters in GH can be used to convert data from one type to another (cast). For example if you need to turn a text into a number, you can feed your text into a ***Number*** parameter. If the text cannot be converted, you'll get an error.

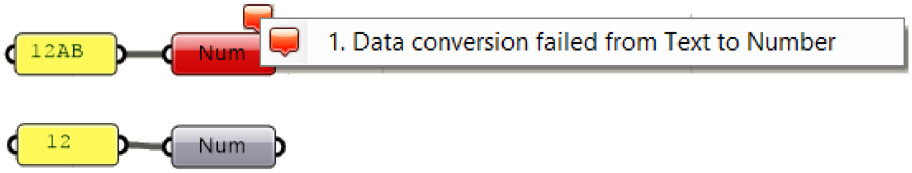


Figure (9): Data conversion (casting) inside parameters in Grasshopper

Grasshopper components internally convert input to suitable types when possible. For example, if you feed a “text” to ***Addition*** component, GH tries to read the text as a number. If a component can process more than one type, it uses the input type without conversion. For example, equality in an expression can compare text as well as numbers. In such cases, make sure you use the intended type to avoid confusion.

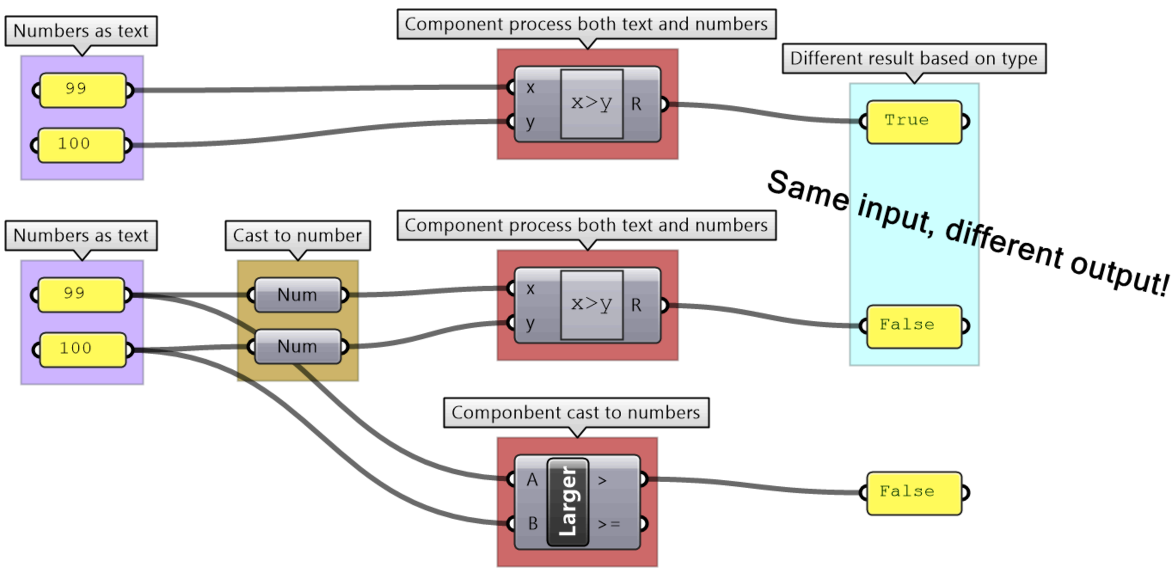


Figure (10): Some operations can be performed on multiple types. Cast to the intended type especially if the component is capable of processing multiple types (such as ***Expression*** in GH)

It is worth noting that sometimes GH components simply ignore invalid input (null or wrong type). In such cases, you are likely to end up with an unexpected result and it will be hard to find the bug. It is very important to verify the output from each component before using it.

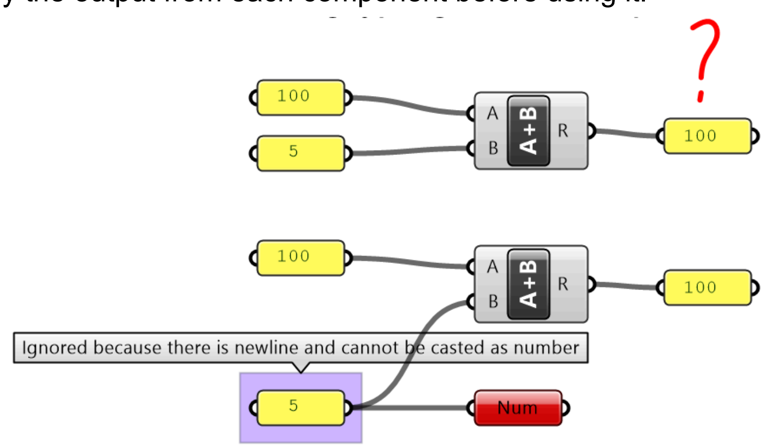


Figure (11): Invalid input is ignored and a default value is used. For example a number inside a ***Panel*** component can be interpreted as a text and hence become invalid input to an ***Addition*** component

1_7: Processing data

Algorithmic designs use many data operations and processes. In the context of this book, we will focus on five categories: numeric and logical operations, analysis, sorting and selection.

1_7_1: Numeric operations

Numeric operations include operations such as arithmetic, trigonometry, polynomials and complex numbers. GH has a rich set of numeric operations, and they are mostly found under the ***Math*** tab. There are two main ways to perform operations in GH. First by using designated components for specific operations such as ***Addition***, ***Subtraction*** and ***Multiplication***.

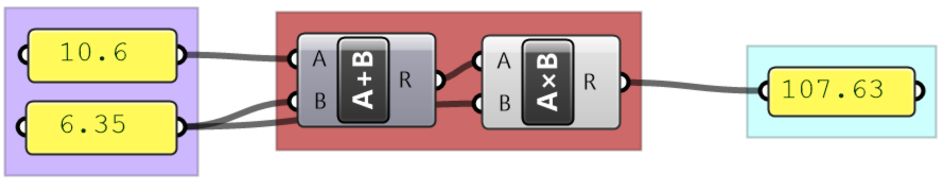


Figure (12): Examples of numeric operations components in GH

Second, use an ***Expression*** component where you can combine multiple operations and perform a rich set of math and trigonometry operations, all in one expression.

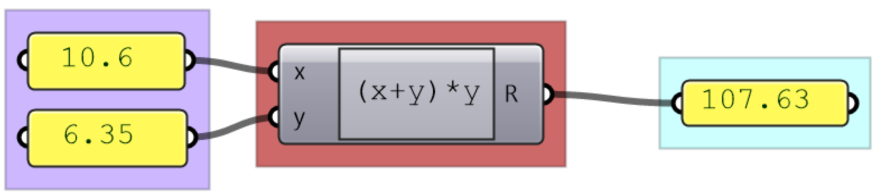


Figure (13): ***Expression*** component in GH can be used to perform multiple operations

The ***Expression*** component is more robust and readable when you have multiple operations.

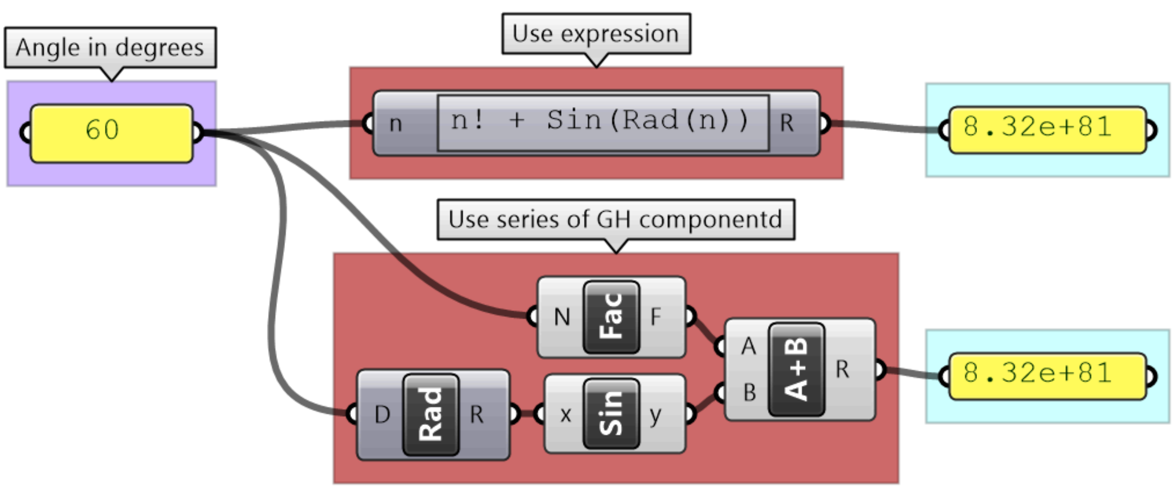


Figure (14): When a chain of operations is involved, using the ***Expression component is*** easier to maintain

Input to Expressions can be treated as text depending on the context.

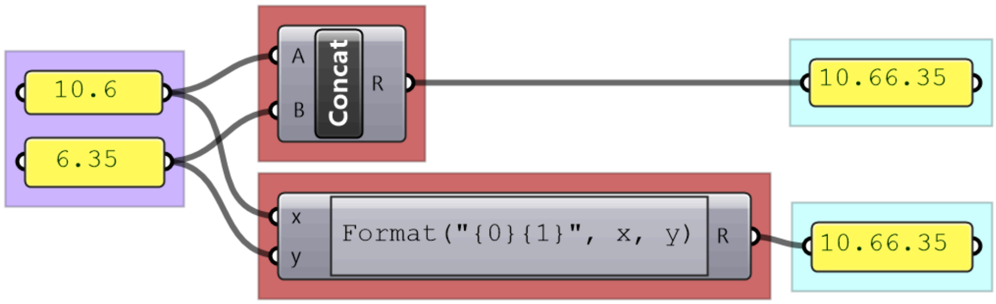


Figure (15): ***Expression*** can process and format text

It is worth mentioning that most numeric input to components allow writing an expression to modify the inputs inline. For example, the Range component has N (number of steps) input. If you right mouse click on “N”, you can set an expression. You always use “x” to represent the supplied input regardless of the name.

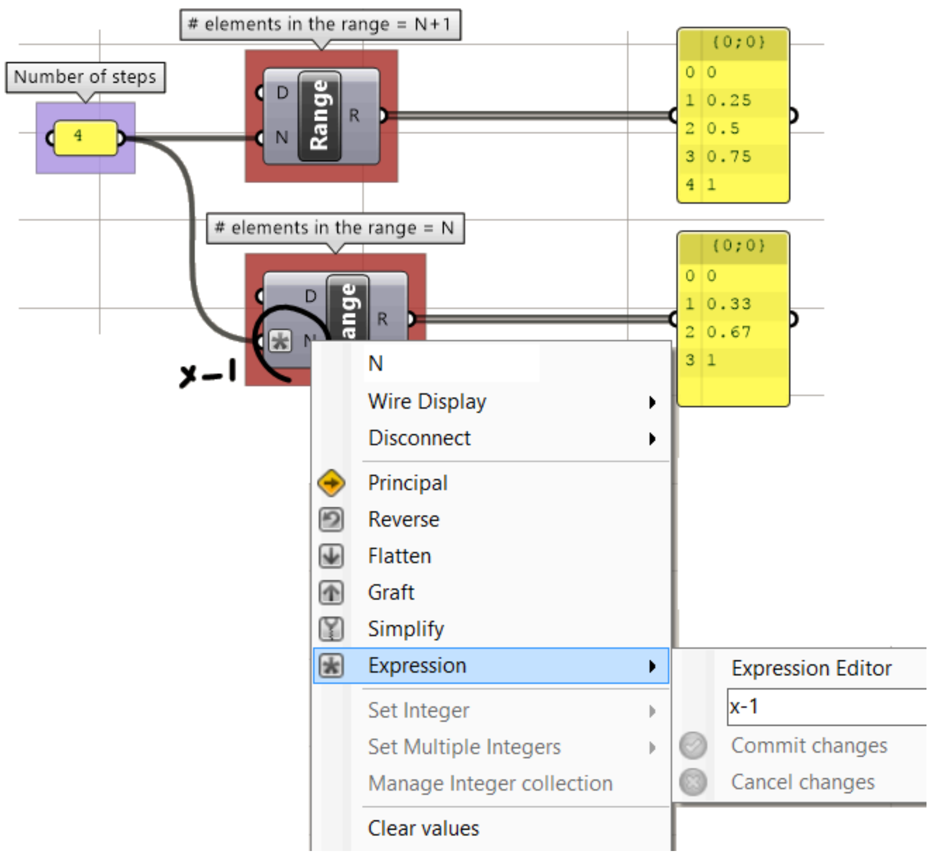


Figure (16): Expression can be set inside the input parameter. Variable “x” refers to the supplied input value

1_7_2: Logical operations

Main logical operations in GH include equalities, sets and logic gates.

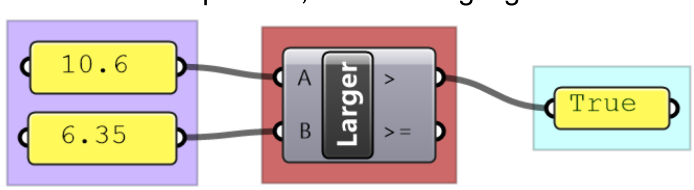


Figure (17): GH has multiple components to perform Logical operations

Logical operations are used to create conditional flow of data. For example, if you like to draw a sphere only when the radius is between two values, then you need to create a logic that blocks the radius when it is not within your limits.

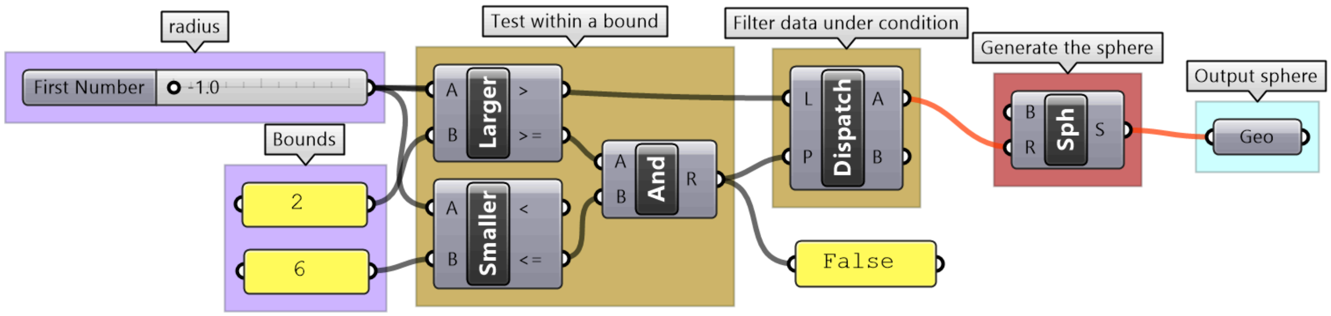


Figure (18): Data flow control using logical operations

1_7_3: Data analysis

There are many tools in GH to examine and preview data. ***Panel*** is used to show the full details of the data and its structure, while the ***Parameter Viewer*** shows the data structure only. Other analysis components include ***Quick Graph*** that plots data in a graph, and ***Bounds*** to find the limits in a given set of numbers (the min and max values in the set).

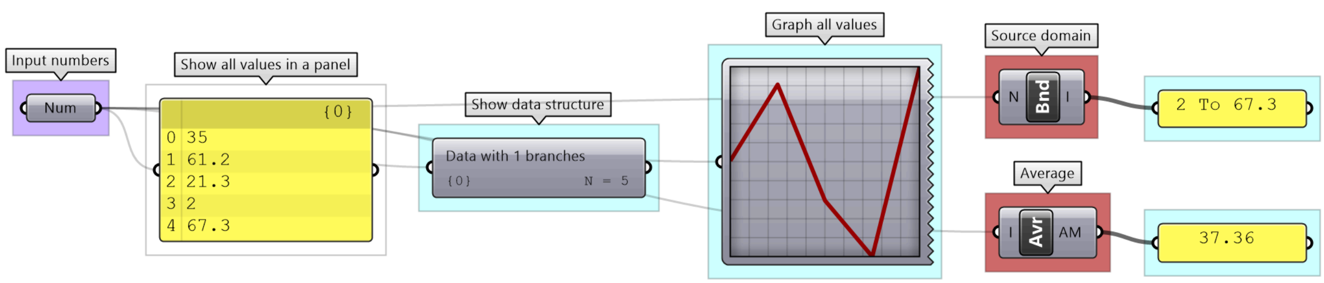


Figure (19): Some of the ways to analyze data in Grasshopper

1_7_4: Sorting

GH has designated components to sort numeric and geometry data. The ***Sort List*** component can sort a list of numeric keys. It can sort a list of numbers in ascending order or reverse the order. You can also use the ***Sort List*** component to sort geometry by some numeric keys, for example sort curves by length. GH has components designated to sort geometry sets such as ***Sort Points*** to sort points by their coordinates.

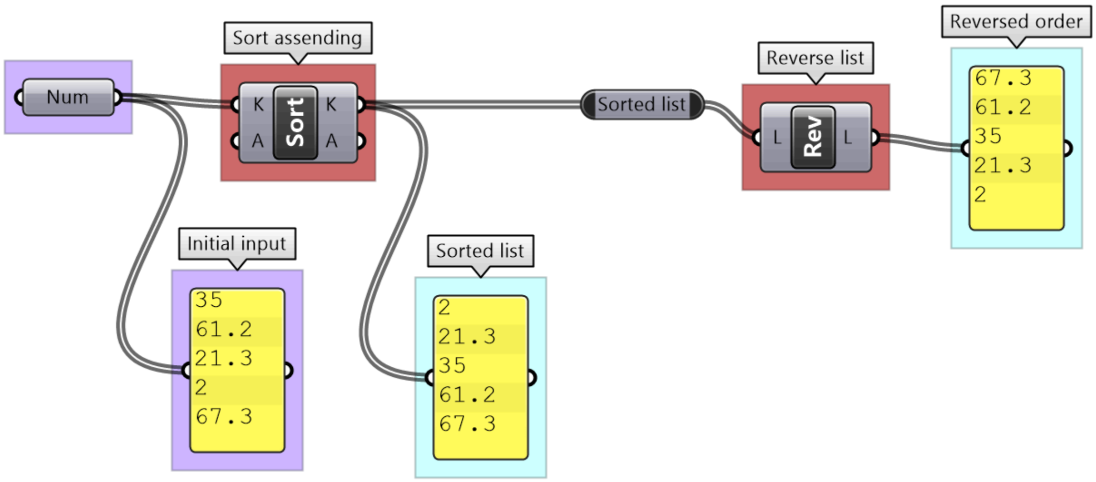


Figure (20): Sorting numbers in Grasshopper

1_7_5: Selection

3D modeling allows picking specific or a group of objects interactively, but this is not possible in algorithmic design. Data is selected in GH based on the location within the data structure, or by a selection pattern. For example ***List Item*** component allows selecting elements based on their indices.

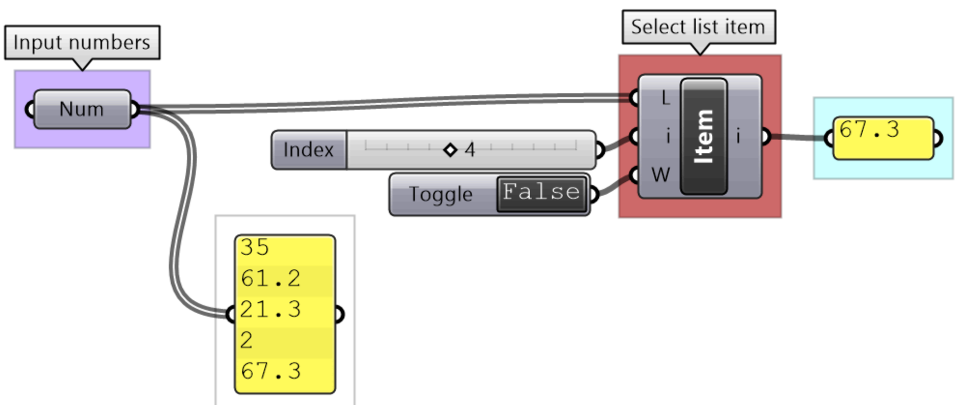


Figure (21): Select items from a list in Grasshopper

The ***Cull Pattern*** component allows using some repeated patterns to select a subset of the data.

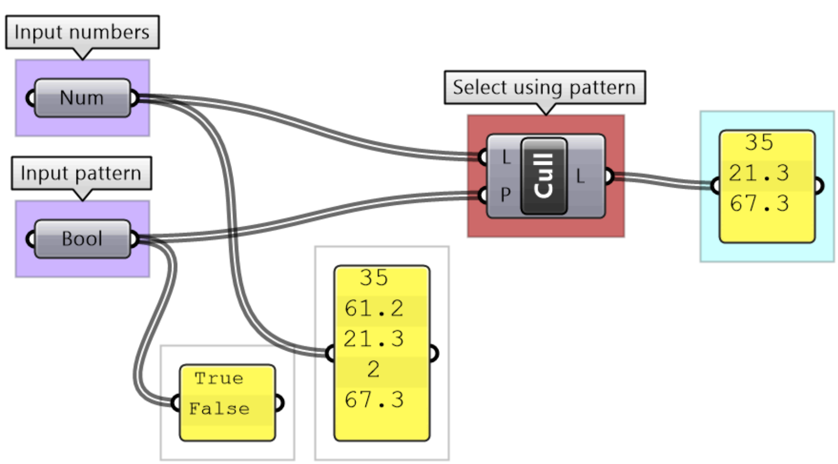


Figure (22): An example to select every other item in a list

As you can see from the examples, selecting specific items or using cull components yield a subset of the data, and the rest is thrown away. Many times you only need to isolate a subset to operate on, then recombine back with the original set. This is possible in GH, but involves more advanced operations. We will get into the details of these operations when we talk about advanced data structures in chapter 3.

1_7_6: Mapping

That refers to the linear mapping of a range of numbers where each number in a set is mapped to exactly one value in the new set. GH has a component to perform linear mapping called ***ReMap***. You can use it to scale a set of numbers from its original range to a new one. This is useful to scale your range to a domain that suits your algorithm's needs and limitations.

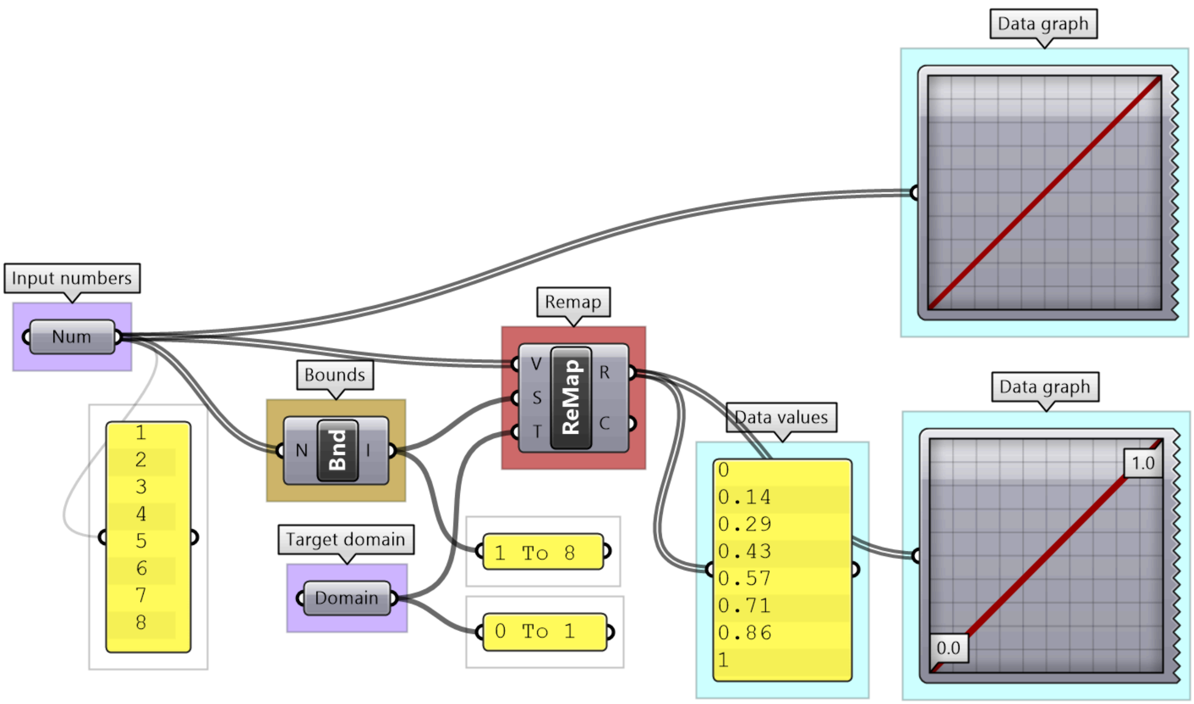


Figure (23): An example of linear remapping of numbers in Grasshopper

Converting data involves mapping. For example, you may need to convert an angle unit from degrees to radians (GH components accept angles in radians only).

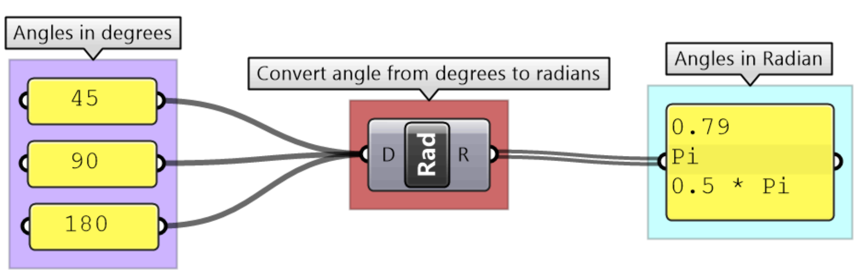


Figure (24): Convert angles from degrees to radians

As you know, parametric curves have "domains" (the range of parameters that evaluate to points on the curve). For example, if the domain of a given curve is between 12.5 to 51.3, evaluating the curve at 12.5 gives the point at the start of the curve. Many times you need to evaluate multiple curves using consistent parameters. Reparameterizing the domain of curves to some unified range helps solve this problem. One common domain to use is “0 To 1”. At the input of each curve in any GH component, there is the option to ***Reparameterize*** which resets the domain of the curve to be “0 to 1”.

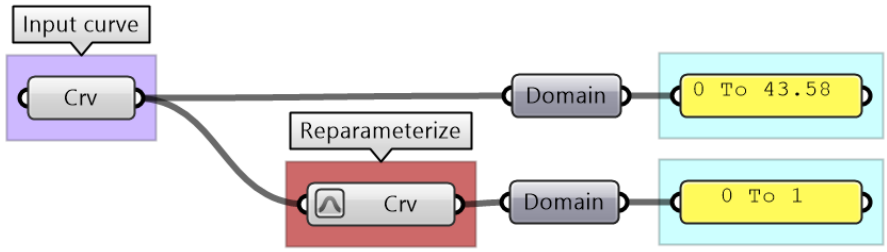
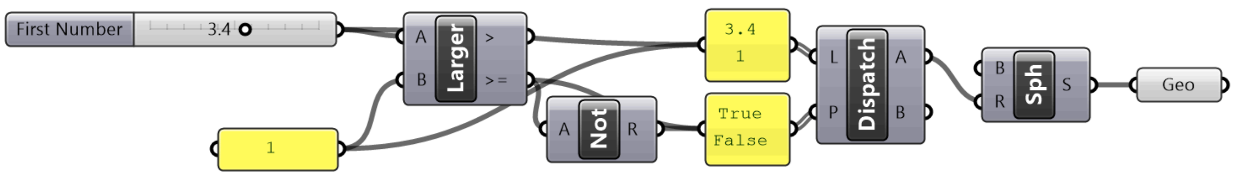


Figure (25): Normalize the domain of curves (set to 0-1). Use Reparameterize input flag in Grasshopper

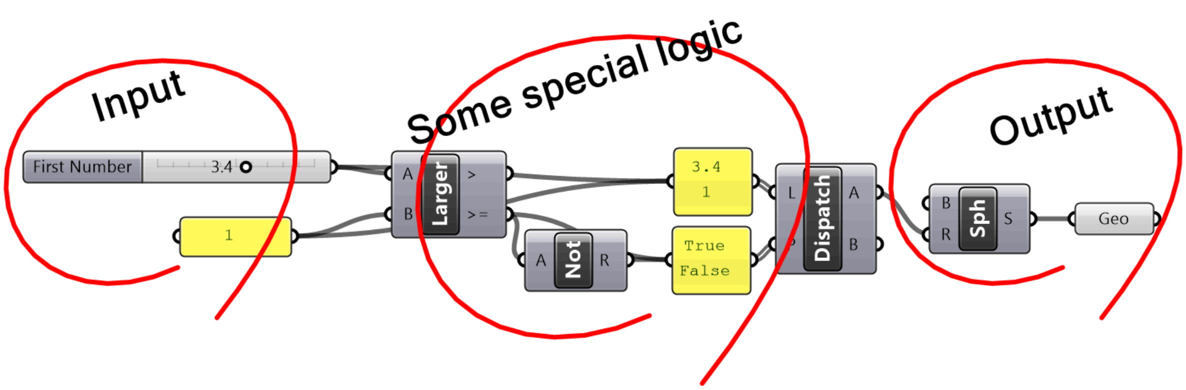
Tutorial 1-7-A: Flow control

What is the purpose of the following algorithm? Notate and color code to describe the purpose of each part.



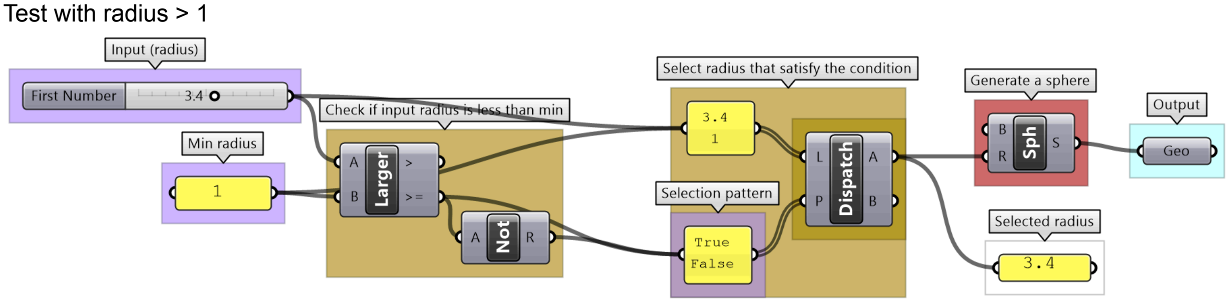
Analyze the algorithm

The algorithm has an output that is a sphere, a radius input and some conditional logic to process the radius.

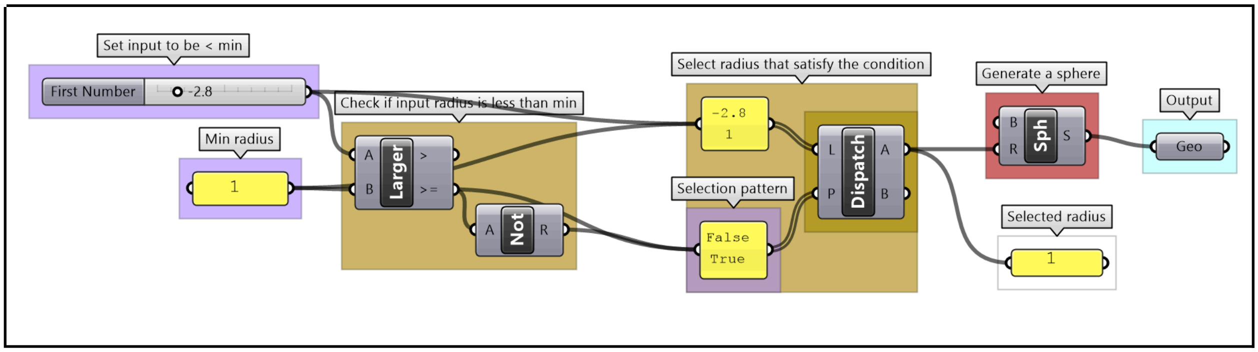


Notate and color-code the solution

From testing the output and following the steps of the solution it becomes apparent that the intention is to make sure that the radius of the sphere cannot be less than 1 unit.
Test with radius > 1



Test with radius < 1



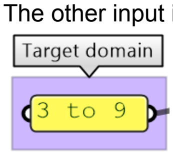
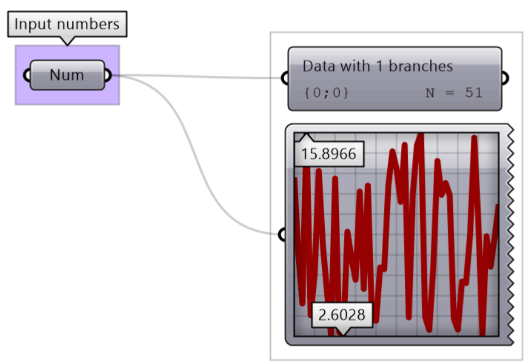
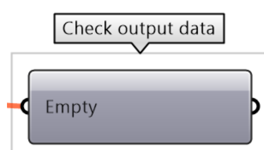
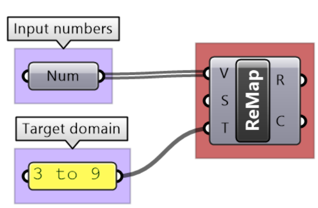
Tutorial 1-7-B: Data processing

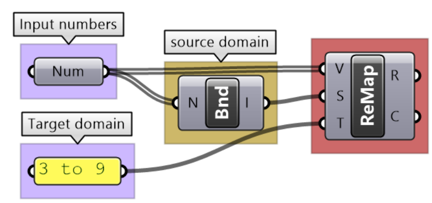
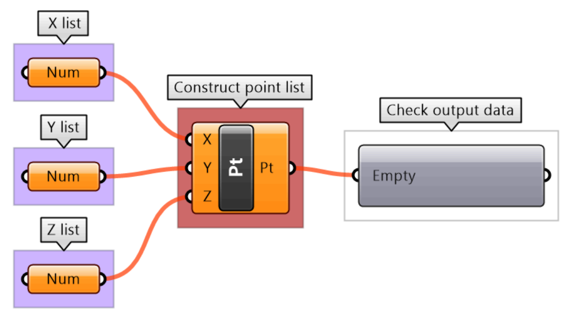
Given a list of point coordinates, do the following:

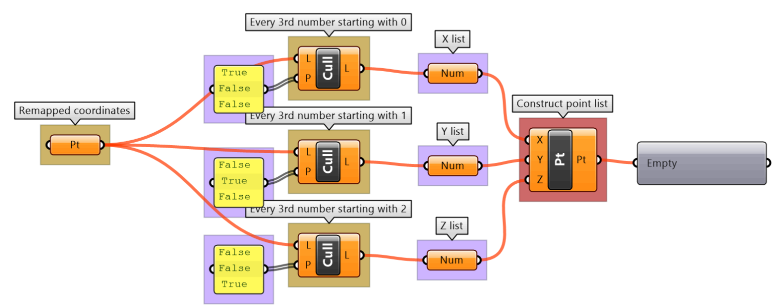
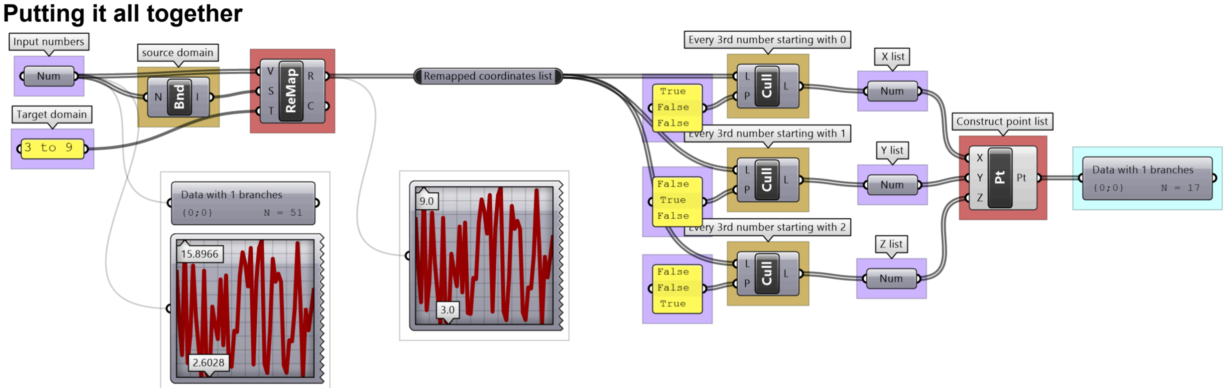
1- Analyze the list to understand the data.

2- Write an algorithm to convert the list of Numbers to a list of Points. Also change the domain of coordinate values to be between 3 and 9.

Note that the input list is organized so that the first 3 numbers refer to the x,y,z of the first point, the second 3 numbers belong to the second point and so on.

Algorithm analysis	
There are 2 inputs: a list of 51 numbers (3 coordinates for each point implies the list includes 17 points) Using a ***QuickGraph,*** we can see that the numbers are between 2.60 and 15.89. We can also see that the values are distributed randomly. The other input is the target domain: 	
Use the 4-step process to solve the algorithms	
Output: List of points Use Parameter Viewer to view the resulting data structure. To start, it will be empty	
Key Process #1 Remap Coordinates: Map the coordinates list from its current domain (2.60 to 15.89) to a new domain (3.0 to 9.0) Use ***ReMap*** component to achieve that	

<table>
<tr>
<td>Intermediate processes #1
The input domain is missing and can be extracted using Bounds component</td>
<td>
</td>
</tr>
<tr>
<td>Key Process #2 Construct Points:
Construct points from coordinates
Use Construct Point (Pt) component</td>
<td>
</td>
</tr>
<tr>
<td>Intermediate processes #2
Extract all X coordinates as one list, Y in another and Z in the third. Use Cull Pattern component with appropriate pattern to extract each coordinate as a separate list.

The input to Cull is the remapped points from process #1</td>
<td>
</td>
</tr>
<tr>
<td colspan="2">Putting it all together

</td>
</tr>
</table>

1_8: Pitfalls of algorithmic design

Writing elegant algorithms that are efficient and easy to read and debug is hard. We explained in this chapter how to write algorithms with style using color-coding and labeling. We also articulated a 4-step process to help develop algorithms. Following these guides help minimize bugs and improve the readability of the scripts. We will list a few of the common issues that lead to incorrect or unintended results.

1_8_1: Invalid or wrong input type

If the input is of the wrong type or is invalid, GH changes the color of components to red or orange to indicate an error warning, with feedback about what the issue might be. This is helpful, but sometimes faulty input goes unnoticed if the components assign a default value, or calculate an alternative value to replace the input, that is not what was intended. It is a good practice to always double check the input (hook to a panel or parameter viewer and label the input). To avoid using wrong types, it is advisable to convert to the intended type to ensure accuracy.

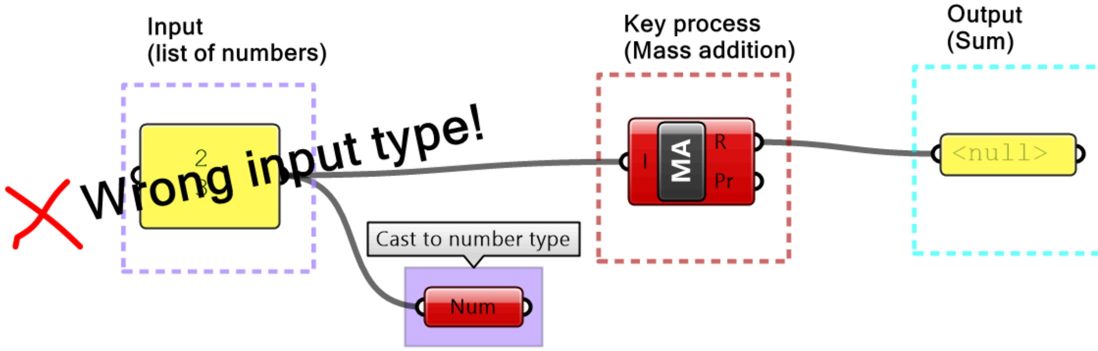


Figure (26): Error resulting from wrong input type

1_8_2: Unintended input

Input is prone to unintended change via intermediate processes or when multiple users have writing access to the script. It is very useful to preview and verify all key input and output. The ***Panel*** component is very versatile and can help check all types of values. Also you can set up guarding logic against out of range values or to trap undesired values.

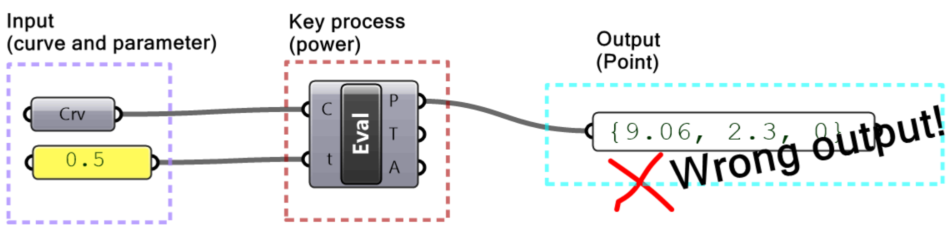


Figure (27): Error resulting from unintended input. Cannot assume curve domain is 0-1 and use 0.5 to evaluate the midpoint.

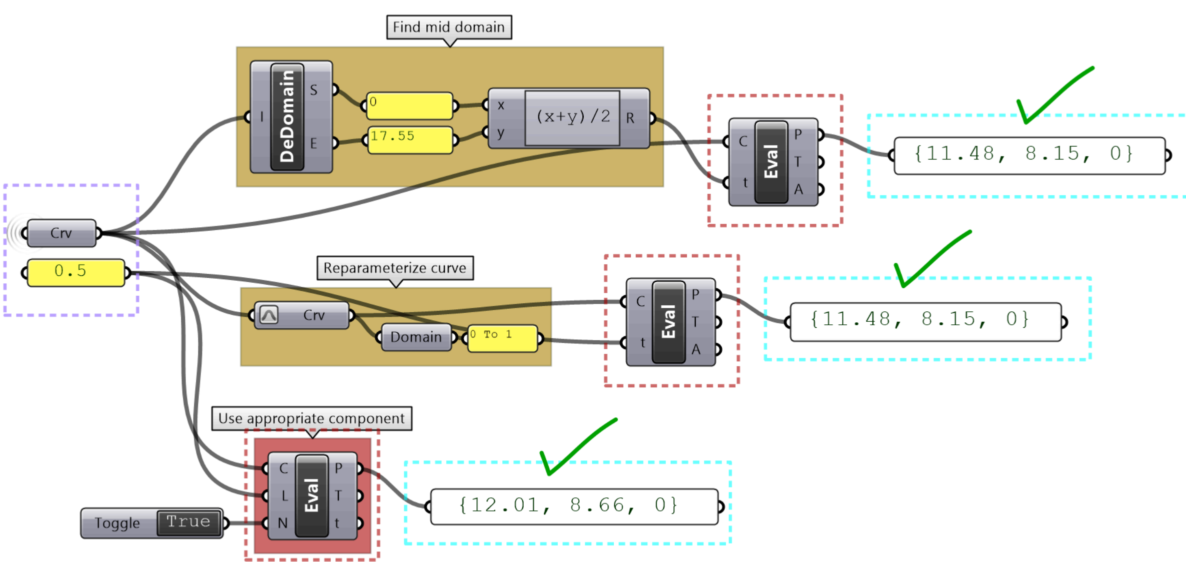


Figure (28): Example of a robust solution to evaluate the midpoint of a curve

1_8_3: Incorrect order of operation

You should try to organize your solutions horizontally or vertically to clearly see the sequence of operations. You should also check the output from each step to make sure it is as expected before continuing on your code. There are also some techniques that help consolidate the script, for example use ***Expression*** when multiple numeric and math operations are involved. The following highlights some unfavorable organization.

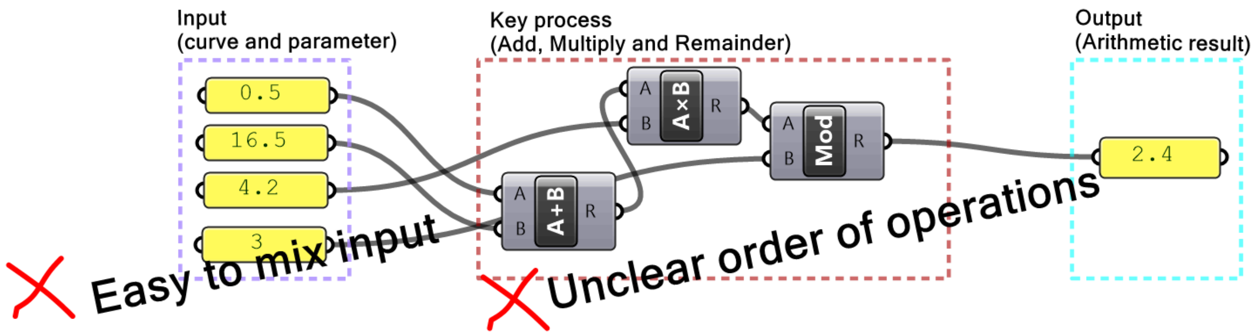


Figure (29): Easy to confuse input to operations with poor organization

The following shows how to rewrite the same code to make it less error prone.

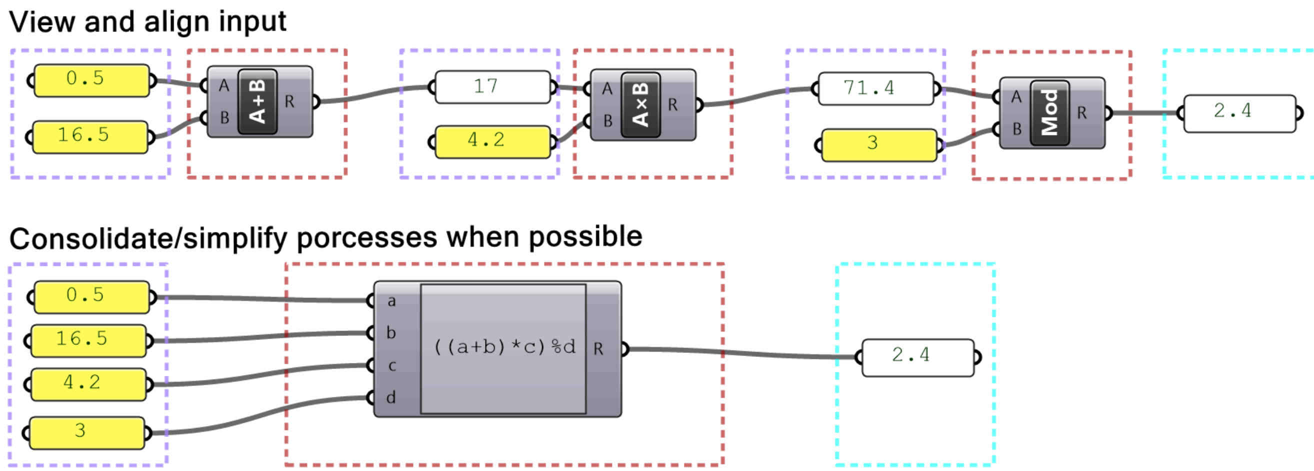


Figure (30): Best practices to align input with processes, or use ***Expressions***

1_8_4: Mismatched data structures

The issue of mismatched data structures as input to the same process or component is particularly tricky to guard against in GH, and has the potential to spiral the solution out of memory. It is essential to test the data structure of all input (except trivial ones) before feeding into any component. It is also important to examine desired matching under different scenarios (data matching will be explained at length later).

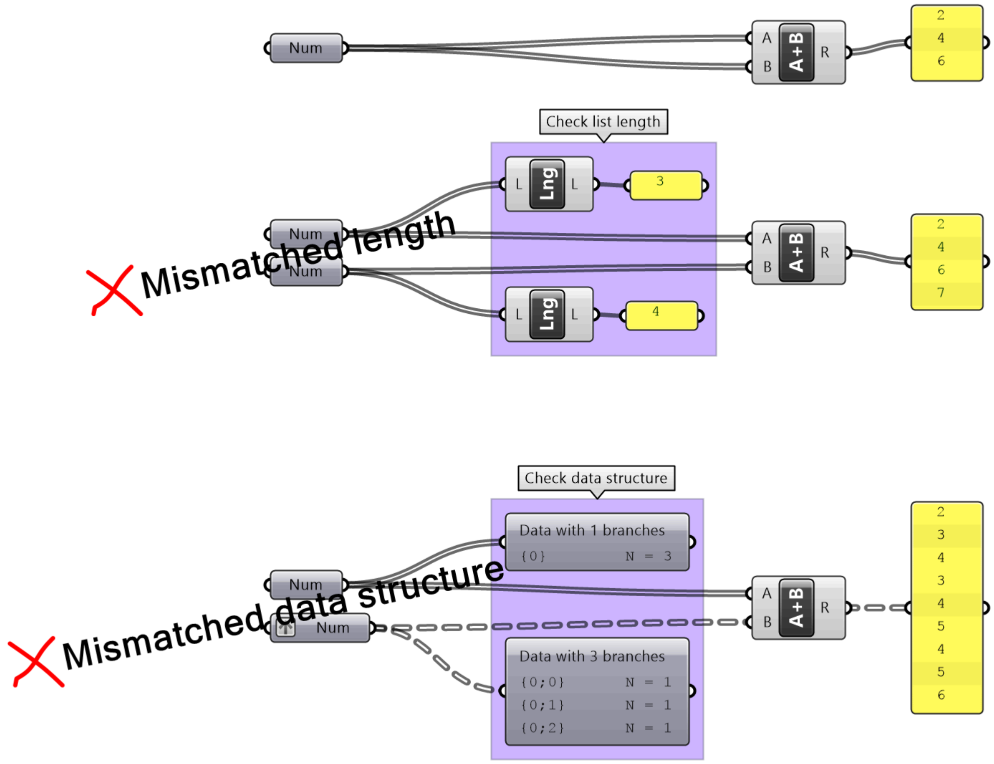


Figure (31): Mismatched data structures of input can cause errors in the output

1_8_5: Long processing time

Some algorithms are time consuming, and you simply have to wait for it to process, but there are ways to minimize the wait when it is unnecessary. For example, at the early cycles of development, you should try to use a smaller set of data to test your solution with before committing the time to process the full set of data. It is also a good practice to break the solution into stages when possible, so you can isolate and disable the time consuming parts. Also, it is often possible to rewrite your solution to be more optimized and consume less time. Use the GH ***Profiler*** to test processing time. When a solution takes far too long to process or crashes, you should do the following: before you reopen the solution, disable it, and disconnect the input that caused the crash.

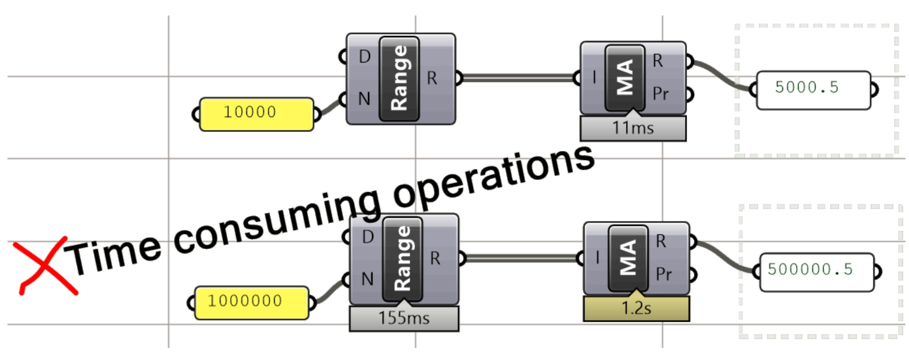


Figure (32): Grasshopper Profiler widget helps observe processing time

1_8_6: Poor organization

Poorly organized definitions are not easy to debug, understand, reuse or modify. We can’t stress enough the importance of writing your definitions with styles, even if it costs extra time to start with. You should always color code, label everything, give meaningful names to variables, break repeated operations into modules and preview your input and output.

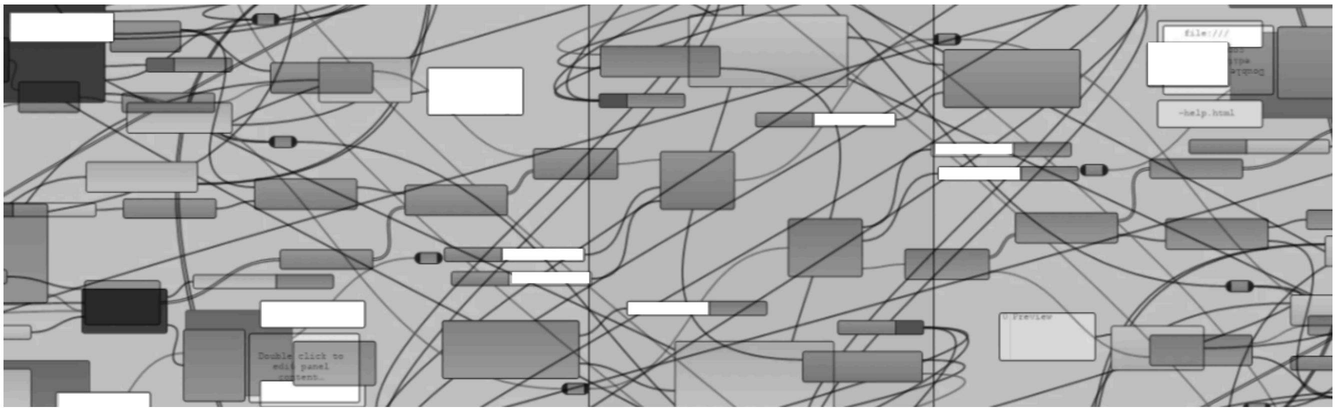


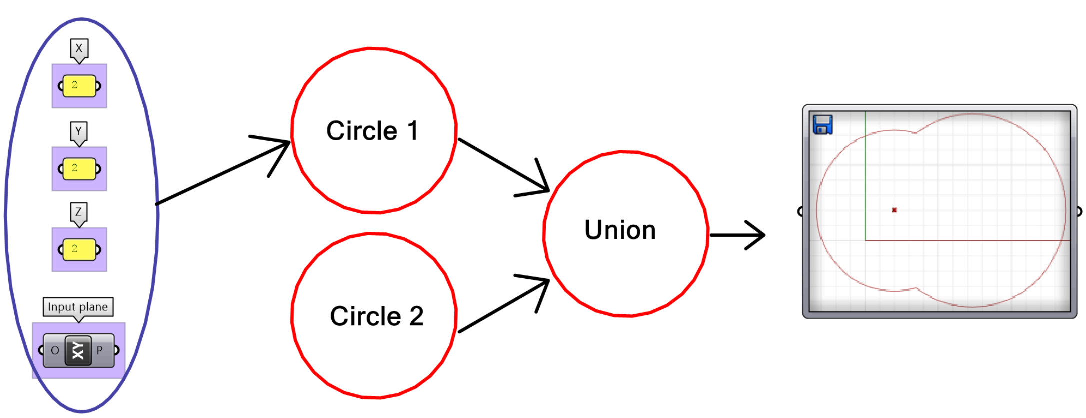
Figure (33): Poor organization in visual programming make the code hard to read and debug

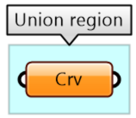
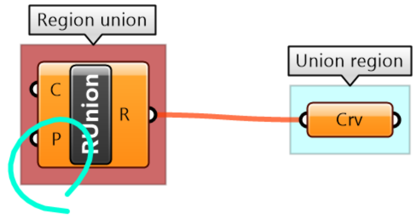
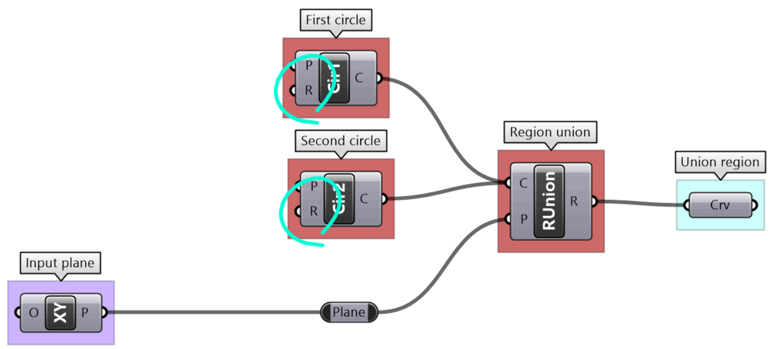
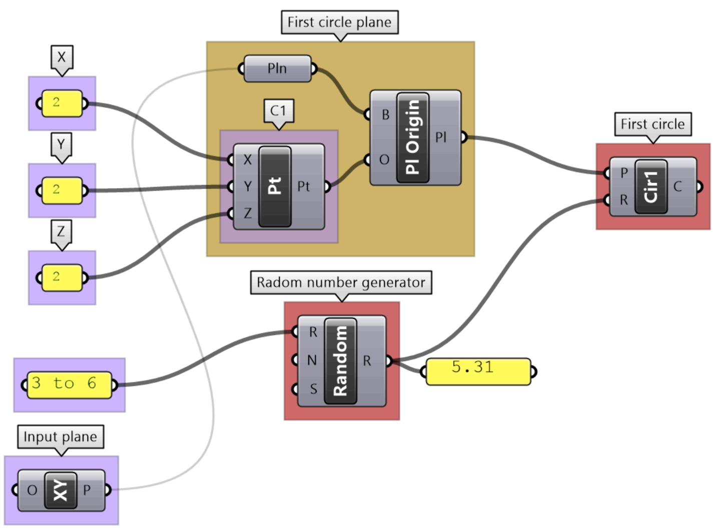
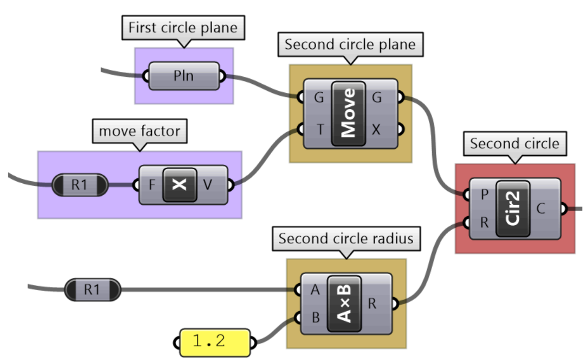
1_9: Algorithms tutorials

1_9_1: Unioned circles tutorial

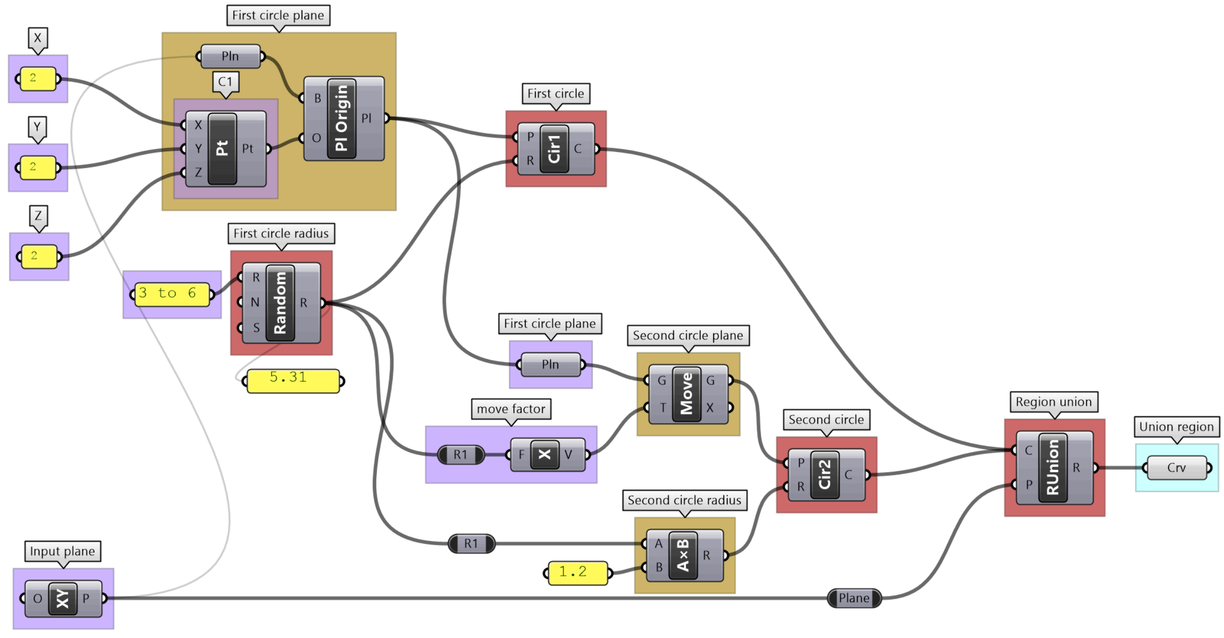
Use the 4-step process to design an algorithm that combines 2 circles, given the following:

Both circles are located on the XY-Plane. The first circle (Cir1) has a center (C1) = (2,2,2) and radius (R1) that is equal to a random number between 3 and 6. The second circle (Cir2) has a center (C2) that is shifted to the right of the first circle (Cir1) by an amount equal to the radius of the first circle (R1) along the positive X-Axis. The second circle radius (R2) is 20% bigger, or in other words (R2) = (R1) * 1.2.

<table>
<tr><th>Analyze the question and the flow of the solution</th></tr>
<tr><td>There are 2 inputs: the coordinates of the center of the first circle (2,2,2) and the XY-Plane where both circles are located. Also, we know that the second circle is shifted the positive X-Axis direction, The following diagram shows an overview of the solution:

</td></tr>
<tr><th>Solution steps</th></tr>
</table>

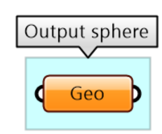
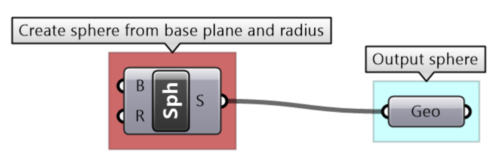
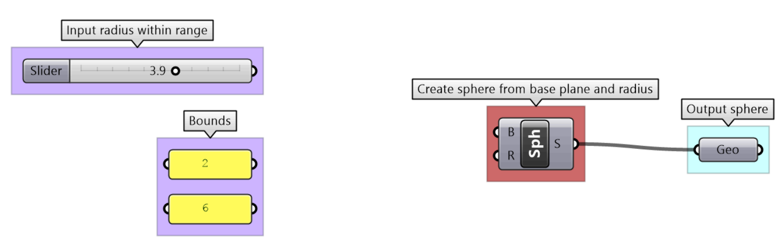
Output Curve for the region union	
Key Process: union of 2 circles Use the ***Region Union*** component that takes curves and a plane	
Input to the region union Identify the input needed and use given input when relevant. The plane for region union has been given. The 2 circles need their own plane and radius. The center of the plane is the center of the circle.	
Intermediate process to generate the center and plane of the 1st circle Construct a center from the given coordinates. Create a plane using ***Plane Origin*** component and use the constructed center and XY-Plane The radius is from a random number between 3 and 6. Use ***Random*** component to create the radius	
Intermediate process to generate the center and plane of the 2nd circle Calculate the 2nd circle plane by moving the first circle plane along the x-axis by an amount = first radius Calculate the 2nd circle radius by multiplying the first radius by 1.2	

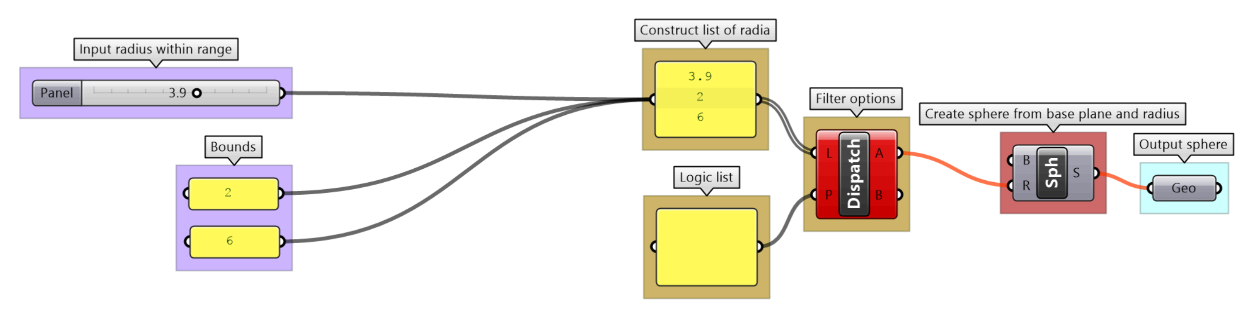
Put it all together



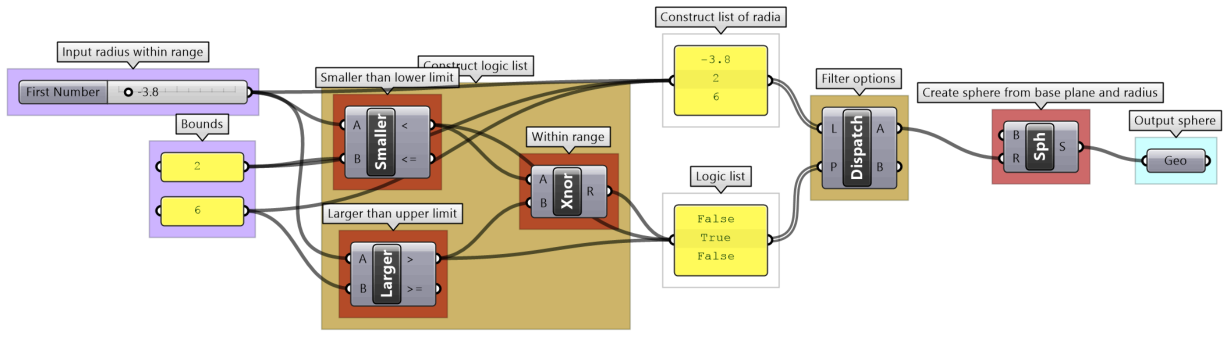
1_9_2: Sphere with bounds tutorial

Use the 4-step process to draw a sphere with a radius between 2 and 6. If input is less than 2, then set the radius to 2, and if input radius is greater than 6, set the radius to 6. Use a number slider to input the radius and set between 0 and 10 to test. Make sure your solution is well organized, color-coded and labeled properly.

The 4-step process to solve the algorithm	
Output The sphere as geometry	
Key Process: create a sphere Use the **Sphere** component to create a sphere from a base plane and radius	
Input 1- The radius parameter (0 - 10) 2- The bounds of the radius are 2 & 6	
Intermediate processes #1 Construct a selection logic of radii and pattern. The radii is a list of the values from the slider, min and max. The list of pattern is generated to select the correct radius value	



Intermediate processes #2
The selection logic ensures that the radius value falls within the intended range. If the radius input is less than the minimum value of the bounds, then the radius is set to the min value, and if it is greater than the maximum, then the max value is used instead.



1_9_3: Data operations tutorial

Given the numbers embedded in the **Number** parameter, do the following:

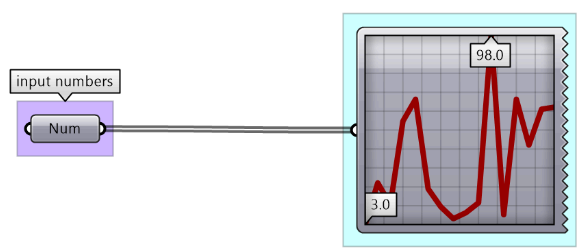
1- Analyze input in terms of bounds and distribution

2- View the data and how it is structured

3- Extract even numbers

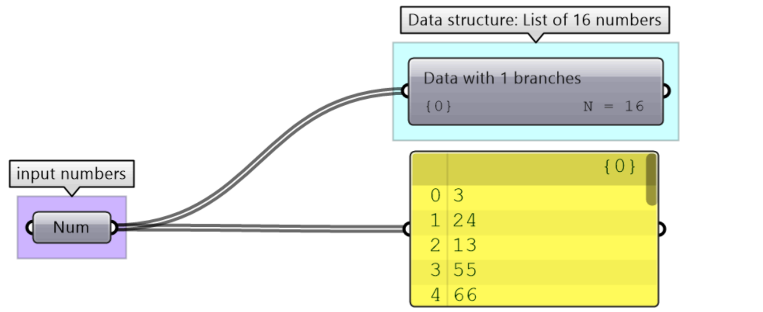
4- Sort numbers descending

5- Remap sorted numbers to (100 to 200)

Solution	
1- Analyze the input bounds and distribution Use the **QuickGraph** to show that the set of numbers are between 3 and 98 and are distributed randomly.	

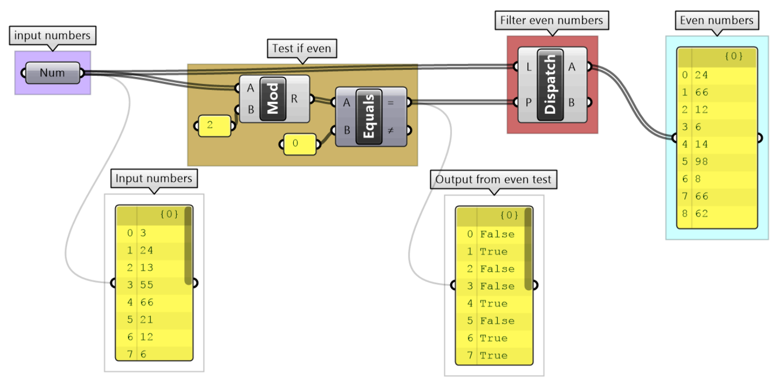
2- Analyze the input data structure and values

Use the ***Panel*** and ***Parameter Viewer*** to show that there are 16 elements organized in a list



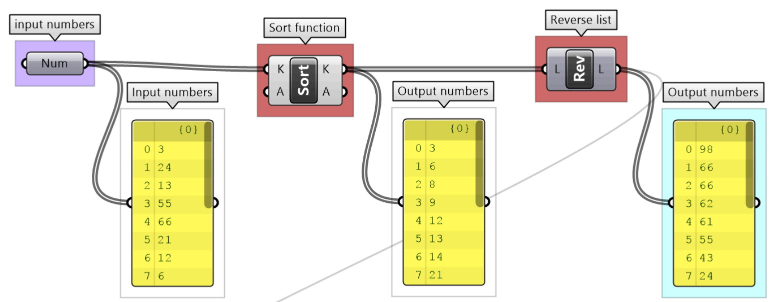
3- Extract Even numbers

Create the logic to test if a number is even (divisible by 2 without a remainder) and use ***Dispatch*** to extract even numbers



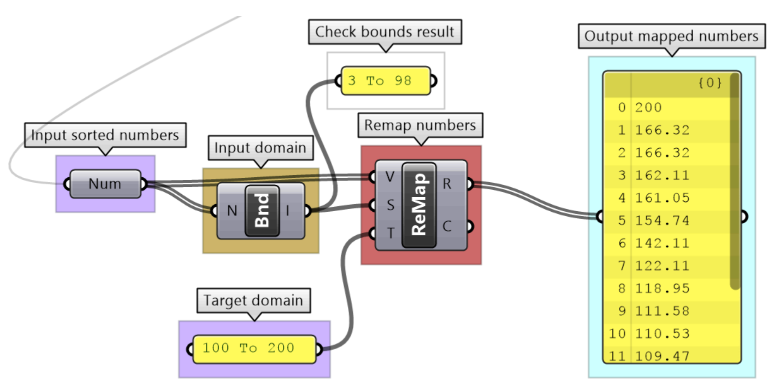
4- Sort numbers descending

The ***Sort List*** component sorts numbers in ascending order. Use ***Reverse List*** component to further process the list to order descending



5- Remap to 100-200

Check the input range and use Remap component to scale data to be between 100-200

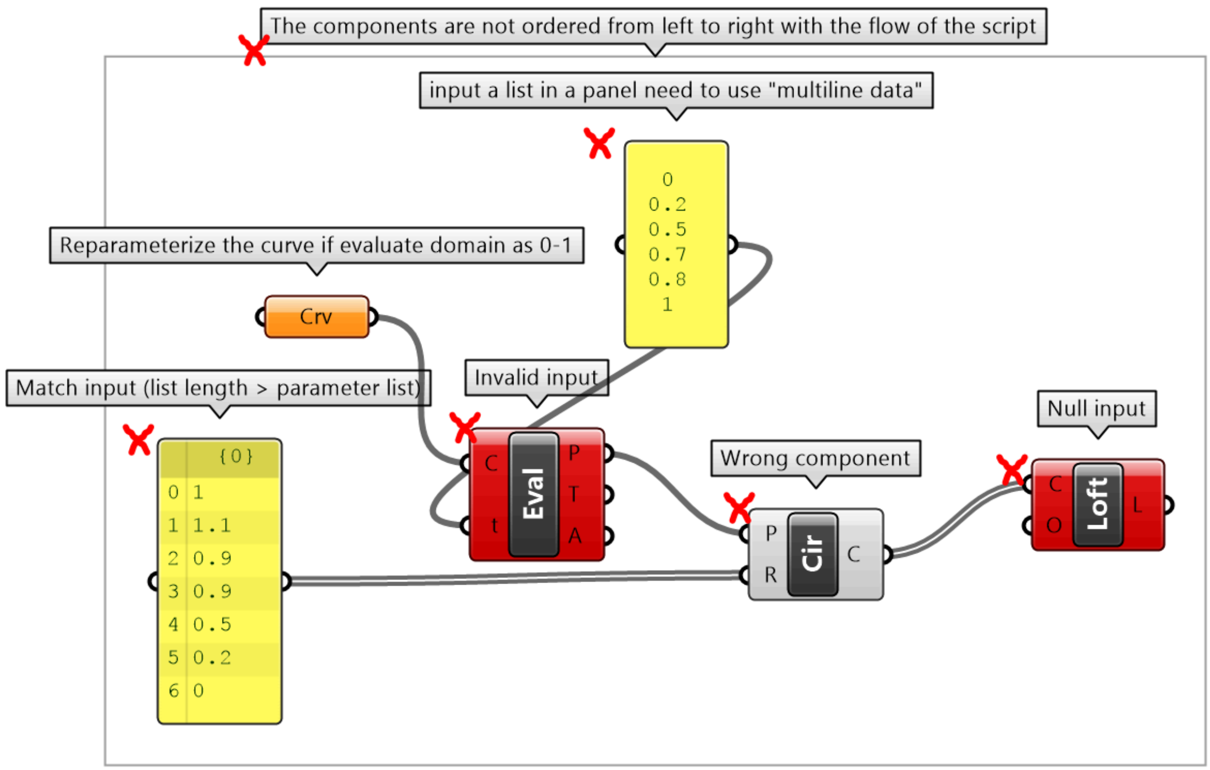


1_9_4: Algorithmic pitfalls tutorial

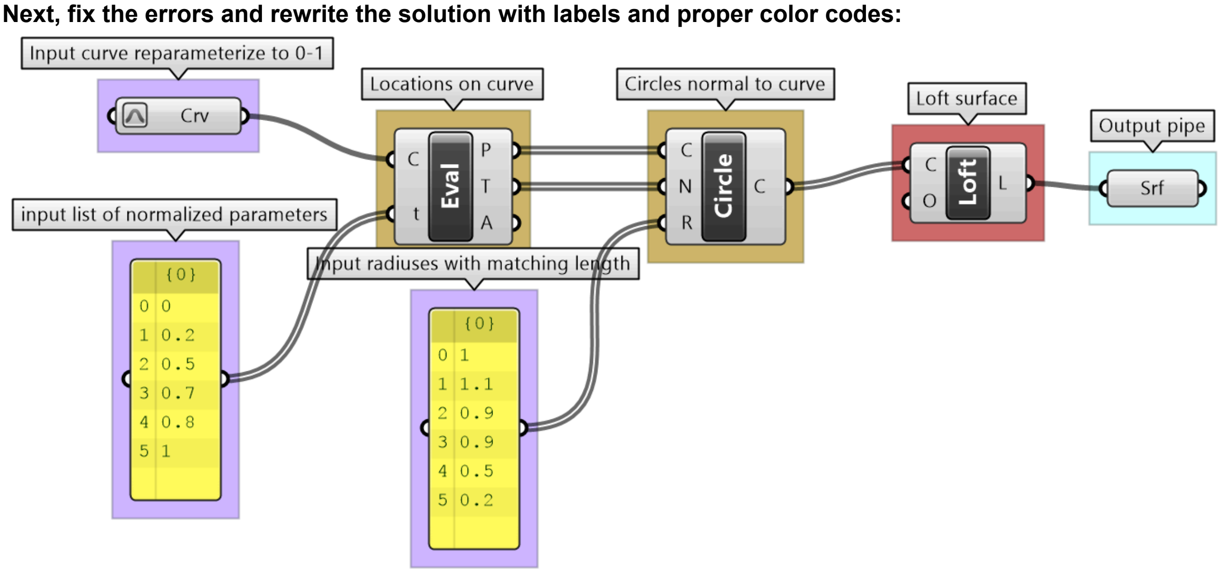
Analyze what the following algorithm is intended to do, identify the errors that are preventing it from working as intended, then rewrite to fix the errors. Organize to reflect the algorithm flow, label and color-code.

Solution

The first step is to mark the errors:



Next, fix the errors and rewrite the solution with labels and proper color codes:



Chapter Two: Introduction to Data Structures

All algorithms involve processing input data to generate a new set of data as output. Data is stored in well-defined structures to help access and manipulate efficiently. Understanding these structures is the key for successful algorithmic designs. This chapter includes an in-depth review of the basic data structures in Grasshopper.

2_1: Overview

Grasshopper has three distinct data structures: **single** item, **list** of items and **tree** of items. GH components execute differently based on input data structures, and hence it is essential to be fully aware of the data structure before using. There are tools in GH to help identify the data structure. Those are ***Panel*** and ***Param Viewer***.

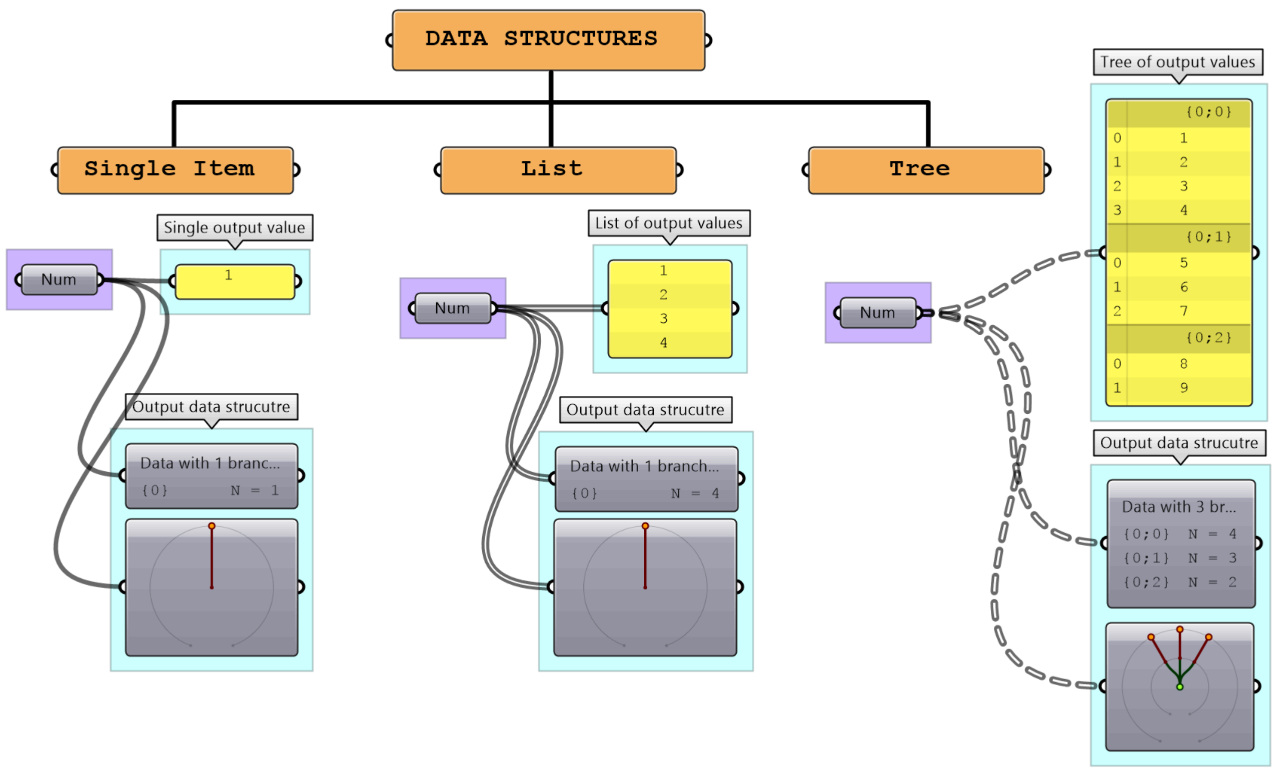


Figure (34): Data structures in Grasshopper

Processes in GH execute differently based on the data structure. For example, the ***Mass Addition*** component adds all the numbers in a list and produces a single number, but when operating on a tree, it produces a list of numbers representing the sum of each branch.

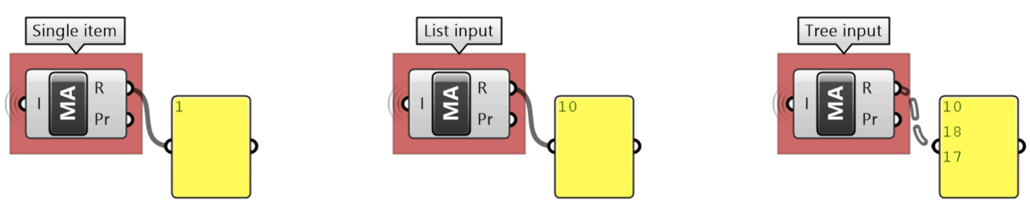
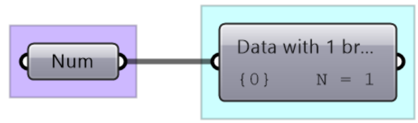
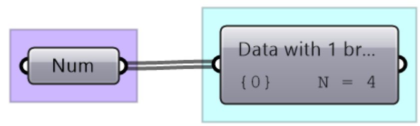
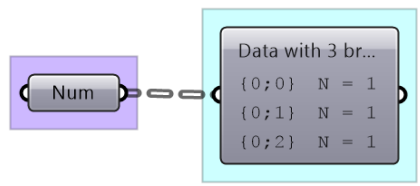


Figure (35): Components execute differently based on the data structures. Result of adding numbers from Figure(34)

The wires connecting the data with components in GH offer additional visual reference to the data structure. The wire from a single item is a simple line, while the wire connecting a list is drawn as a double line. A wire output from a tree data structure is a dashed double line. This is very useful to quickly identify the structure of your data.

Display the data structure	Example
Item: single branch with single item **Wire display**: single line	
List: single branch with multiple items **Wire display**: double line	
Tree: multiple branches with any number of items per branch **Wire display**: double dashed line	

2_2: Generating lists

There are many ways to generate lists of data in GH. So far we have seen how to directly embed a list of values inside a parameter or a panel (with multiline data). There are also special components to generate lists. For example, to generate a list of numbers, there are three key components: ***Range***, ***Series*** and ***Random***. The ***Range*** component creates an equally spaced range of numbers between a min and max values (called domain) and a number of steps (the number of values in the resulting list is equal to the number of steps plus one).

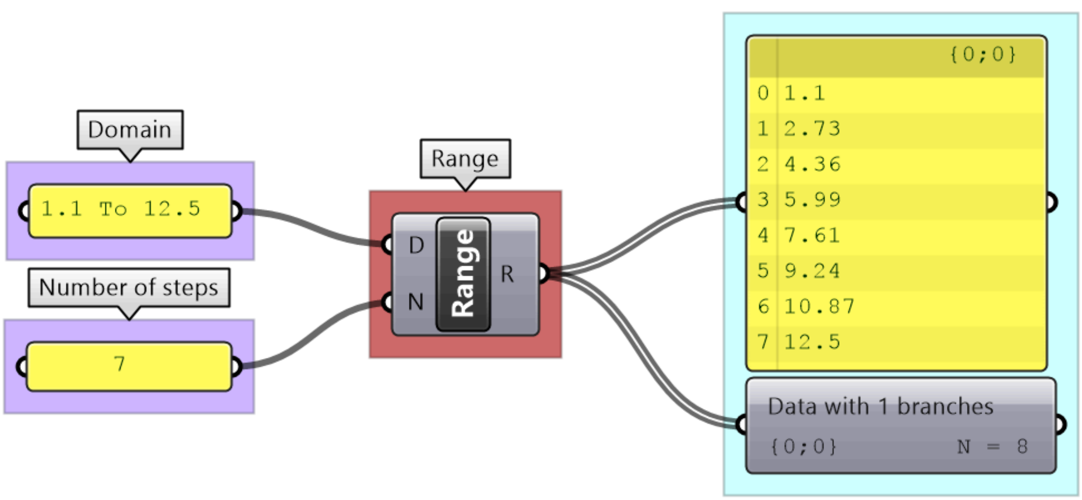


Figure (36): Generate a list of 8 numbers using the ***Range*** component in Grasshopper

The ***Series*** component also creates an equally spaced list of numbers, but here you set the starting number, step size and number of elements.

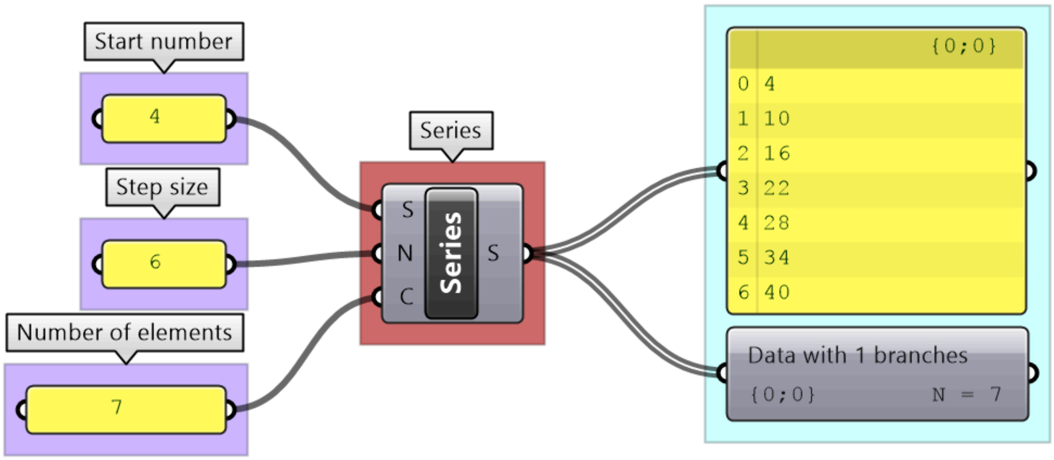


Figure (37): Generate a list of 7 numbers using the ***Series*** component in Grasshopper

The ***Random*** component is used to create random numbers using a domain and a number of elements. If you use the same seed, then you always get the same set of random numbers.

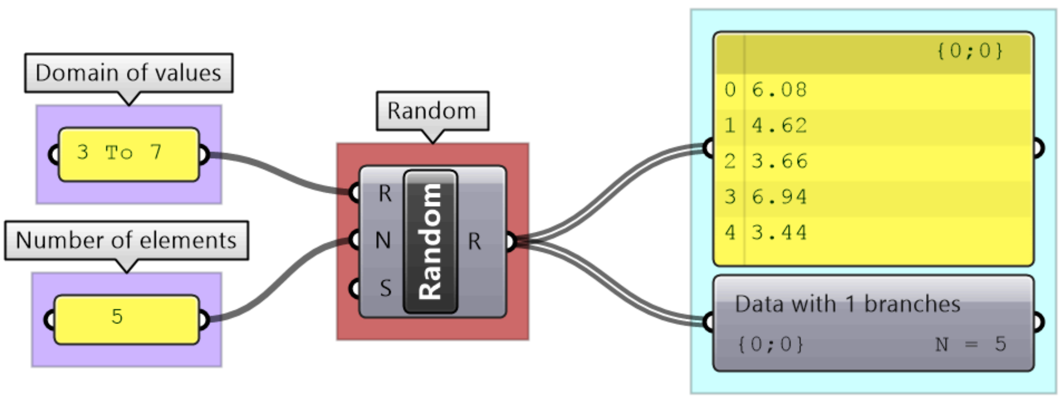


Figure (38): Generate a list of numbers using the ***Random*** component in Grasshopper

Lists can be the output of some components such as ***Divide*** curve (the output includes lists of points, tangents and parameters). Use the ***Panel*** component to preview the values in a list and ***Parameter Viewer*** to examine the data structures.

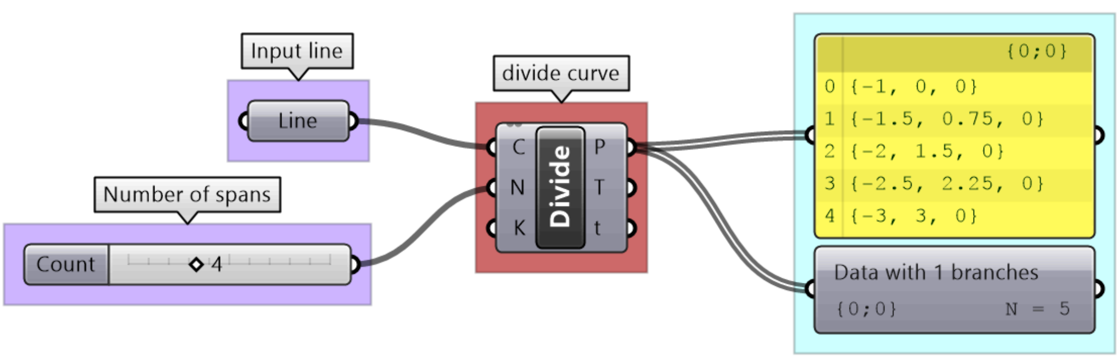
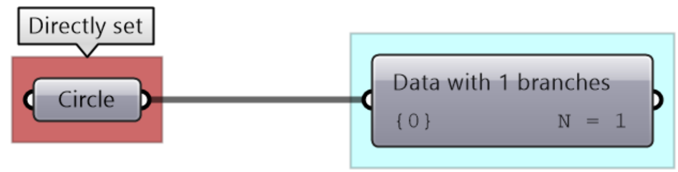
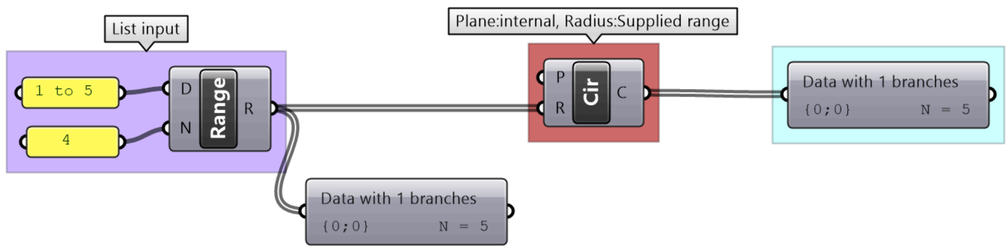
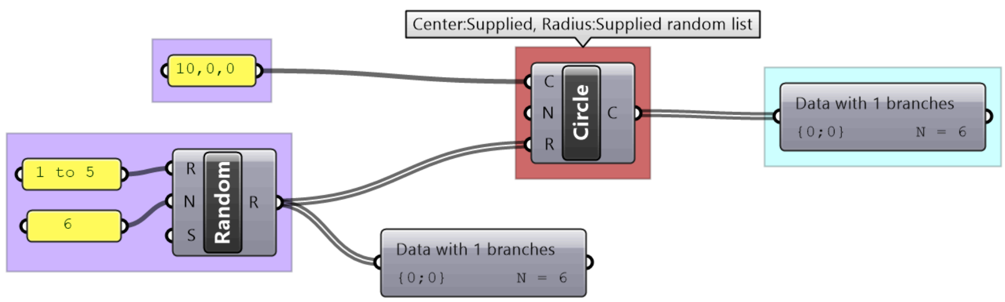
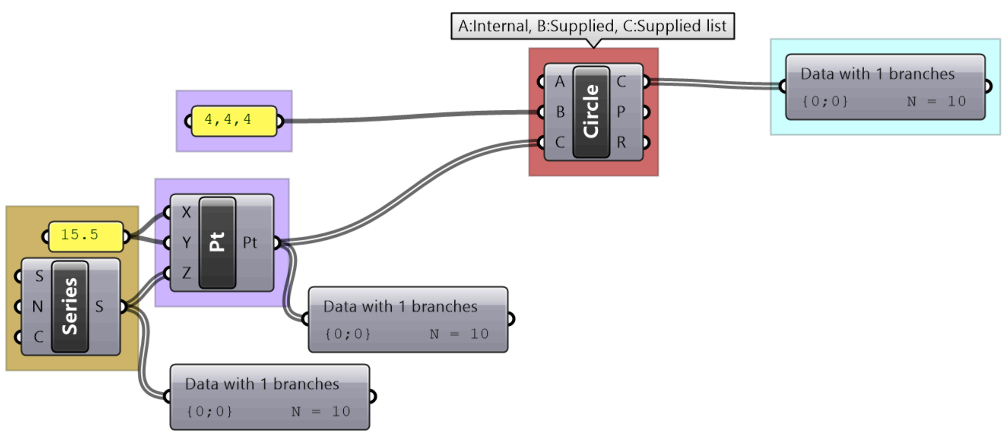


Figure (39): ***Divide Curve*** takes a single input (curve) and generate lists of output

2_2_1 Generating lists tutorial

Explore 4 different ways to create circles. Use different data sources and data structures.

Description	Grasshopper solution
Directly set a circle in a parameter	
Set the plane input to the default XY-Plane (internal). Supply a list of radiuses using ***Range*** component	
Supply one value for the center. Normal is set to default (internal) List of radiuses using ***Random*** component	
Create a circle from 3 points: A: set internally to one value B: Supply one value C: Supply a list of values using the ***Series*** component to set a list of Z coordinates	

2_3: List operations

Grasshopper offers an extensive list of components for list operations and list management. We will review the most commonly used ones.
You can check the length of a list using the ***List Length*** component, and access items at specific indices using the ***List Item*** component.

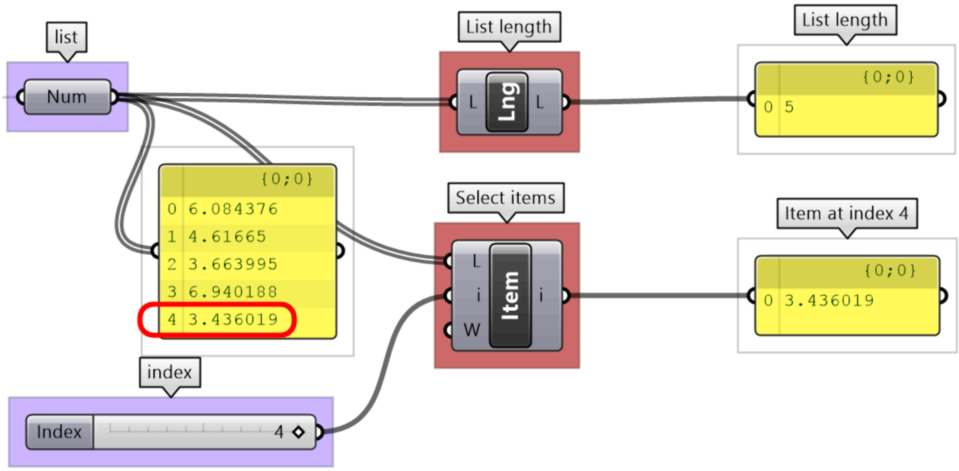


Figure (40): Examples of list operations in Grasshopper

Lists can be reversed using the ***Reverse List*** component, and sorted using the ***Sort List*** component.

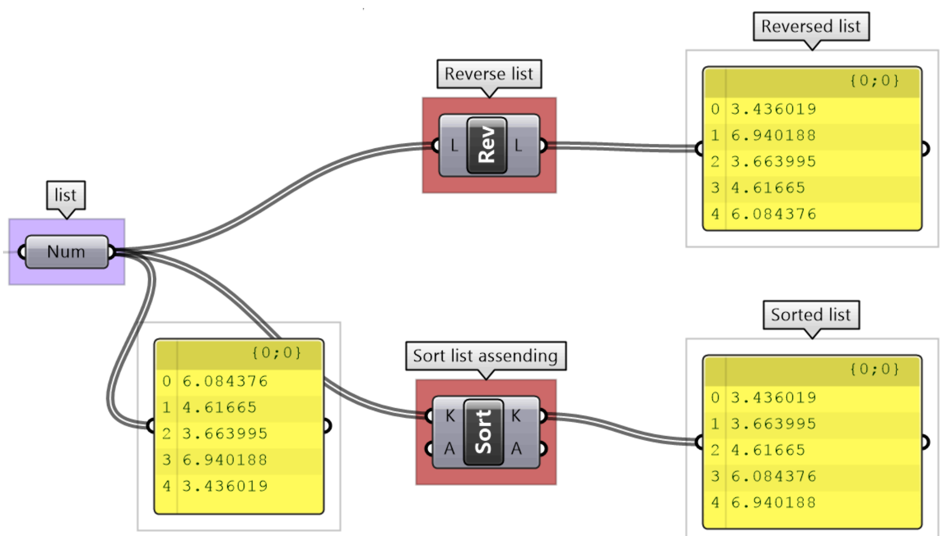


Figure (41): Lists can be reversed or sorted using designated components in Grasshopper

Components such as ***Cull Patterns*** and ***Dispatch*** allow selecting a subset of the list, or splitting the list based on a pattern.These components are very commonly used to control data flow and select a subset of the data.

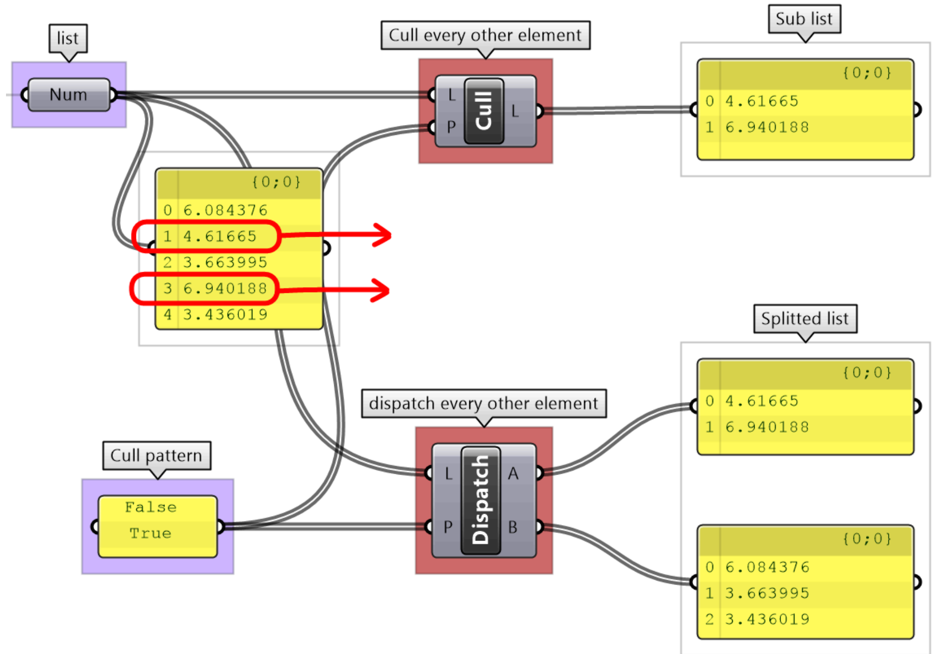


Figure (42): Cull part of a list using components such as ***Cull Pattern*** and ***Dispatch***

The ***Shift List*** component allows shifting a list by any number of steps. That helps align multiple lists to match in a particular order.

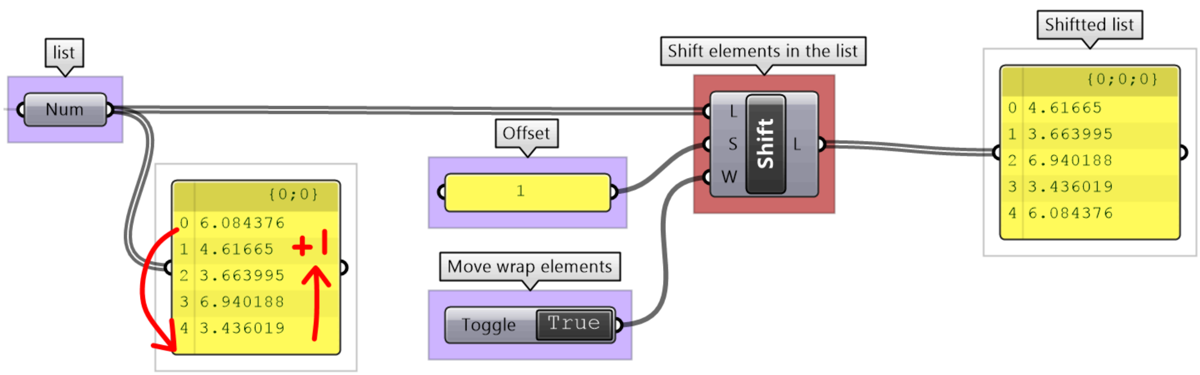


Figure (43): ***Shift*** operation in Grasshopper

The ***Subset*** component is another example to select part of a list based on a range of indices.

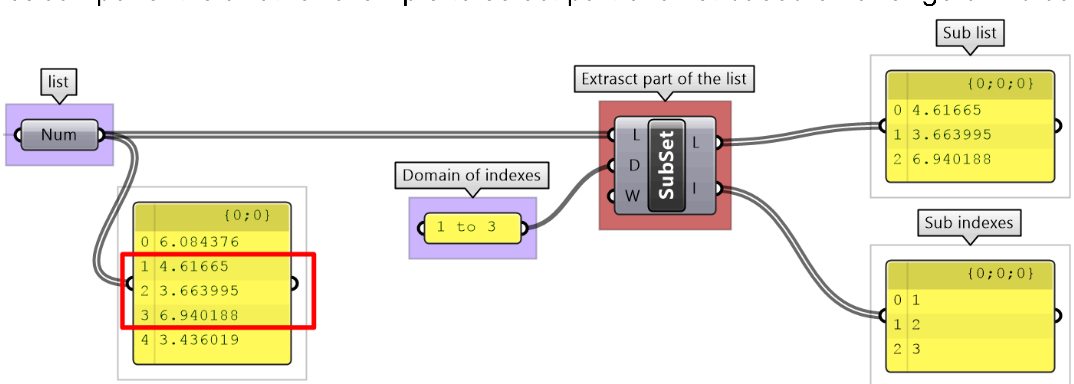
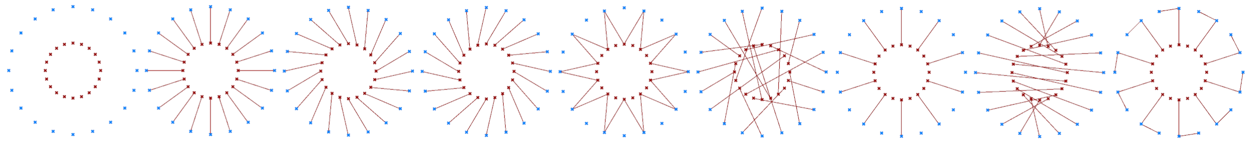
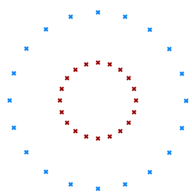
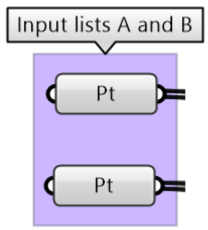
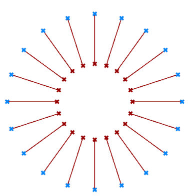
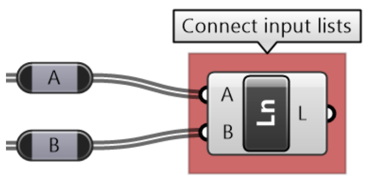
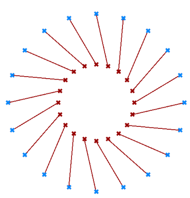
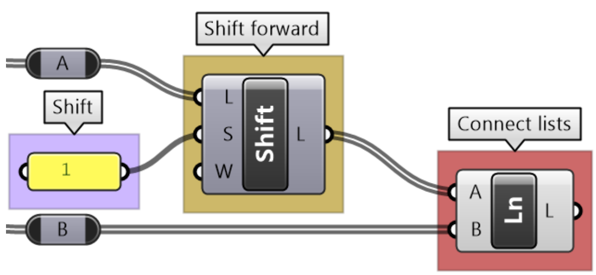
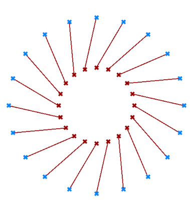
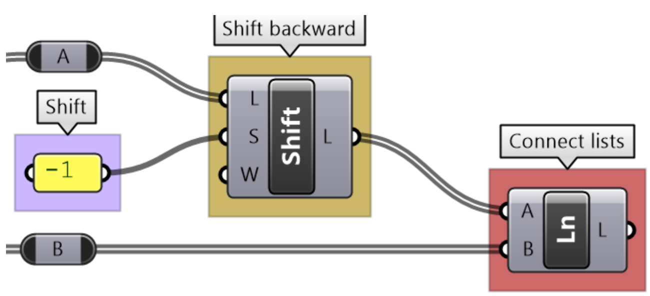


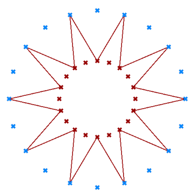
Figure (44): Select a subset of the list using a range of indices

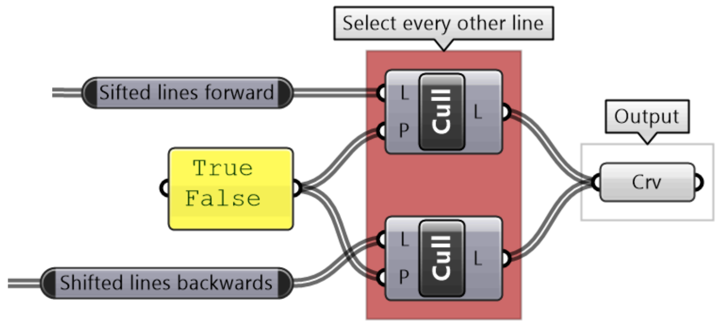
2_3_1 List operations tutorial

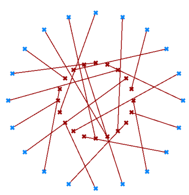
Given two lists of points from dividing two concentric circles, generate the following patterns.

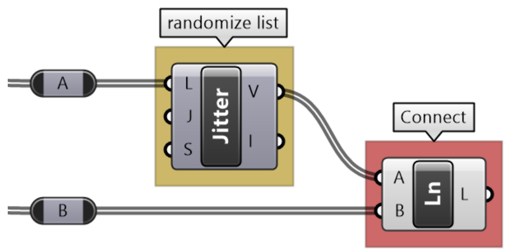


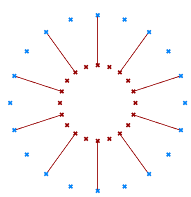
<table>
<tr><th>Output image</th><th>Grasshopper solution</th></tr>
<tr><td></td><td>
</td></tr>
<tr><td></td><td>
</td></tr>
<tr><td></td><td>
</td></tr>
<tr><td></td><td>
</td></tr>
</table>

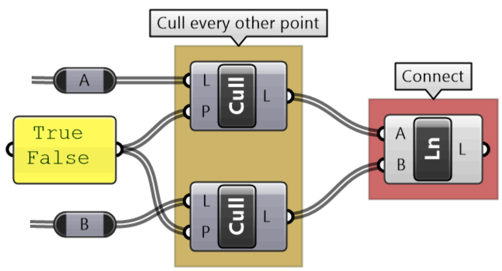


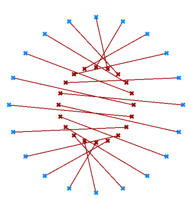

Select every other line
Sifted lines forward
True
False
Shifted lines backwards
L
P
Cull
L
Output
Crv

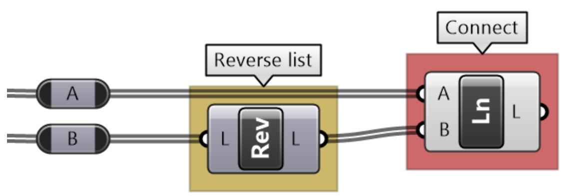


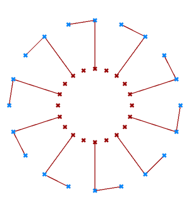

randomize list
A
L
J
S
Jitter
V
I
Connect
A
B
Ln
L
B

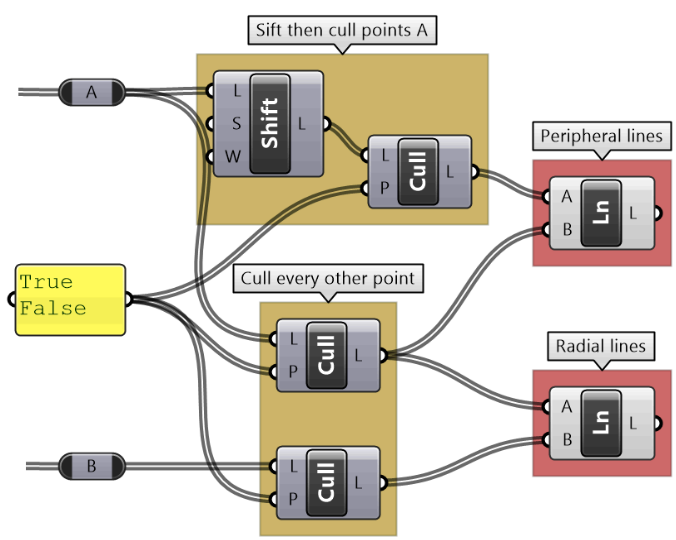



Cull every other point
A
True
False
B
L
P
Cull
L
Connect
A
B
Ln
L




Connect
Reverse list
A
B
L
Rev
L
A
B
Ln
L




Sift then cull points A
A
L
S
W
Shift
L
L
P
Cull
L
Peripheral lines
A
B
Ln
L
True
False
Cull every other point
L
P
Cull
L
Radial lines
A
B
Ln
L
B

2_4: List matching

When the input is a single item or has an equal number of elements in a simple list, it is easy to imagine how the data is matched. The matching is based on corresponding indices. Let's use the ***Addition*** component to examine list matching in GH. Note that the same principles apply to all other Grasshopper components.

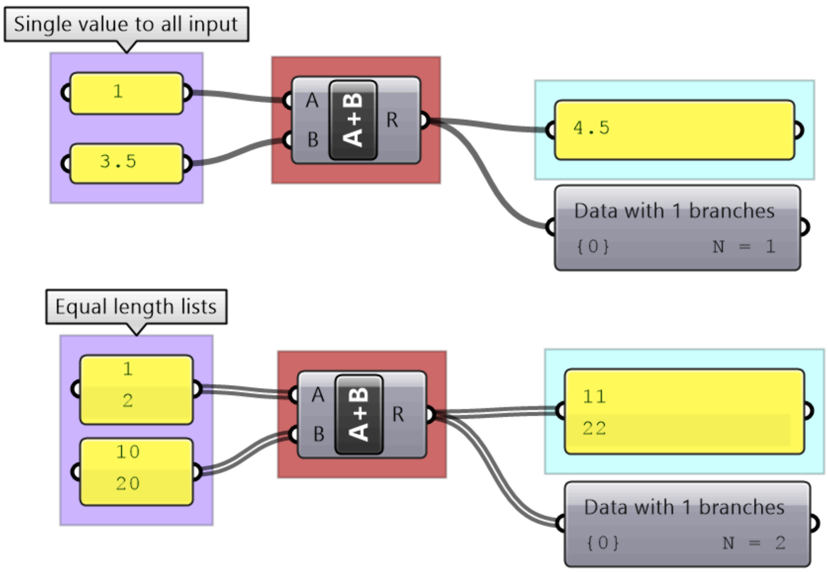


Figure (45): Matching equal length lists is based on matching corresponding indices

There are times when input has variable length lists. In this case, GH reuses the last item on the shorter list and matches it with the next items in the longer list.

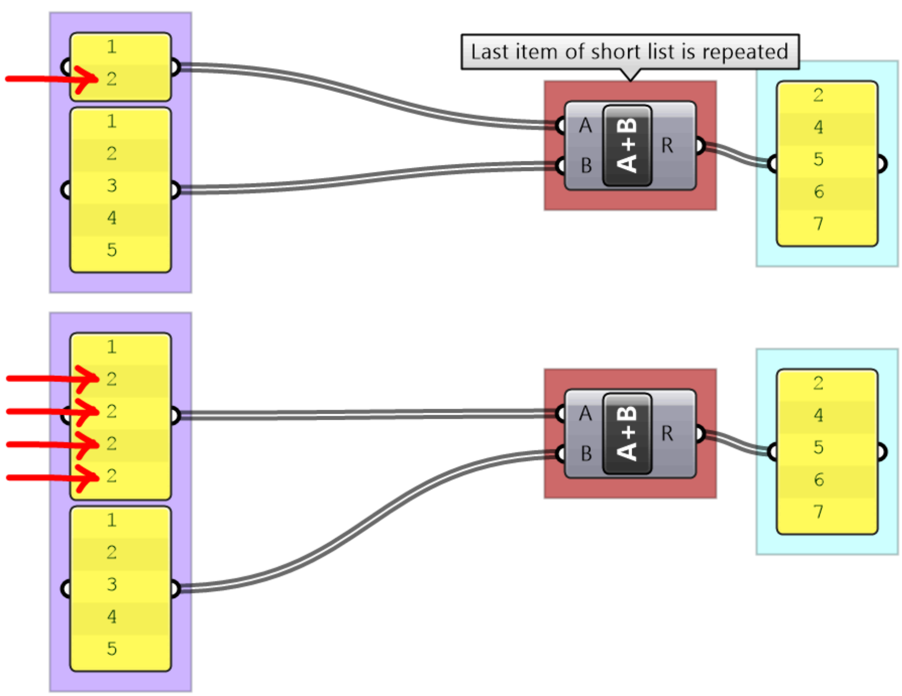


Figure (46): The default list matching in Grasshopper reuses the last element of the shorter list

Grasshopper offers alternative ways of data matching: ***Long***, ***Short*** and ***Cross*** reference that the user can force to use. The ***Long*** matching is the same as the default matching. That is, the last element of the shorter list is repeated to create a matching length.

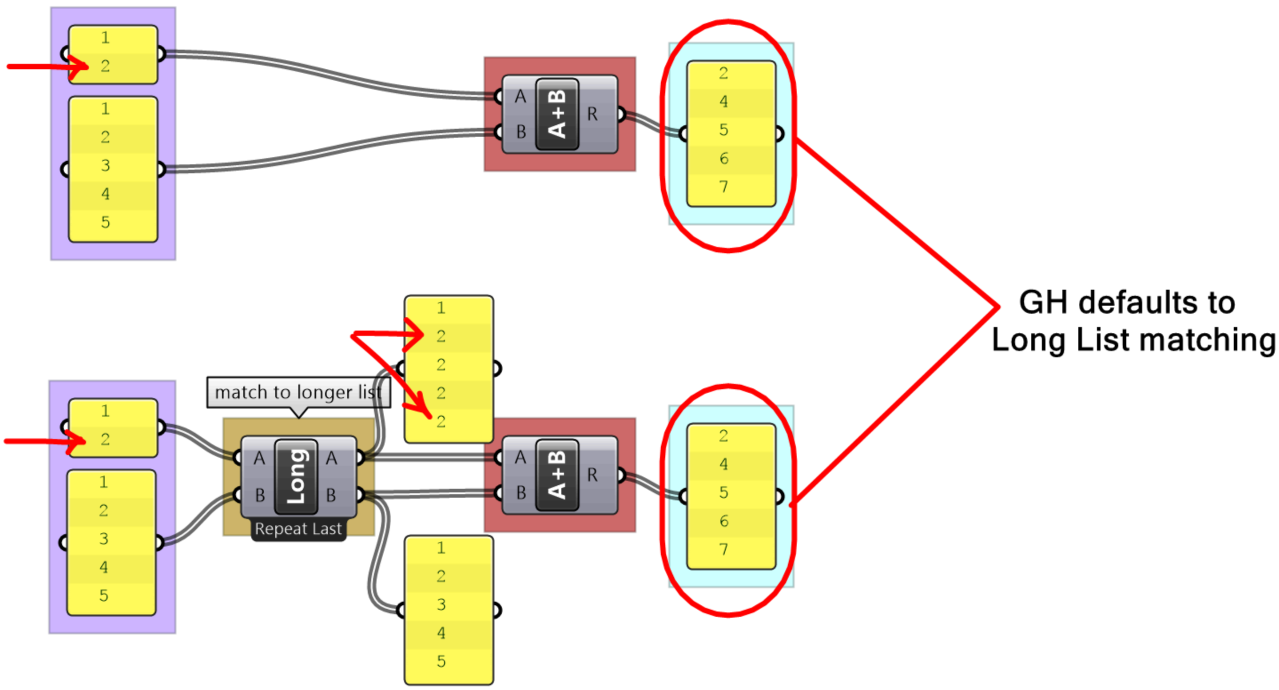


Figure (47): Long list matching is the default matching mode in Grasshopper

The ***Short*** list matching truncates the long list to match the length of the short list. All additional elements are ignored and the resulting list has a length that matches the shorter list.

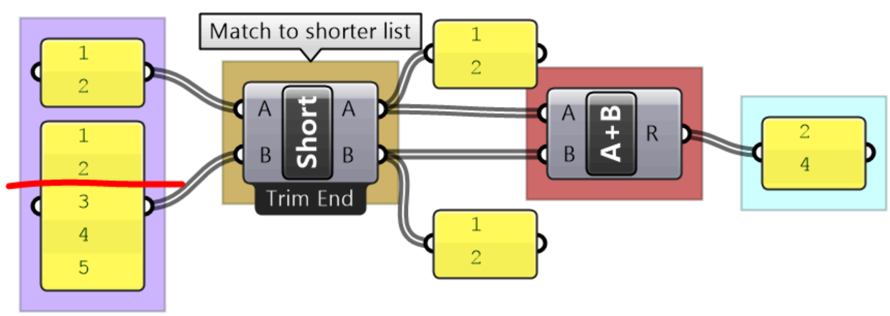


Figure (48): Short matching of lists omits additional values in longer lists

The ***Cross Reference*** matches the first list with each of the elements in the second list. The resulting list has a length equal to the multiplication product of the length of input lists. Cross reference is useful when trying to produce all possible combinations of input data. The order of input affects the order of the result as shown in Figure (49).

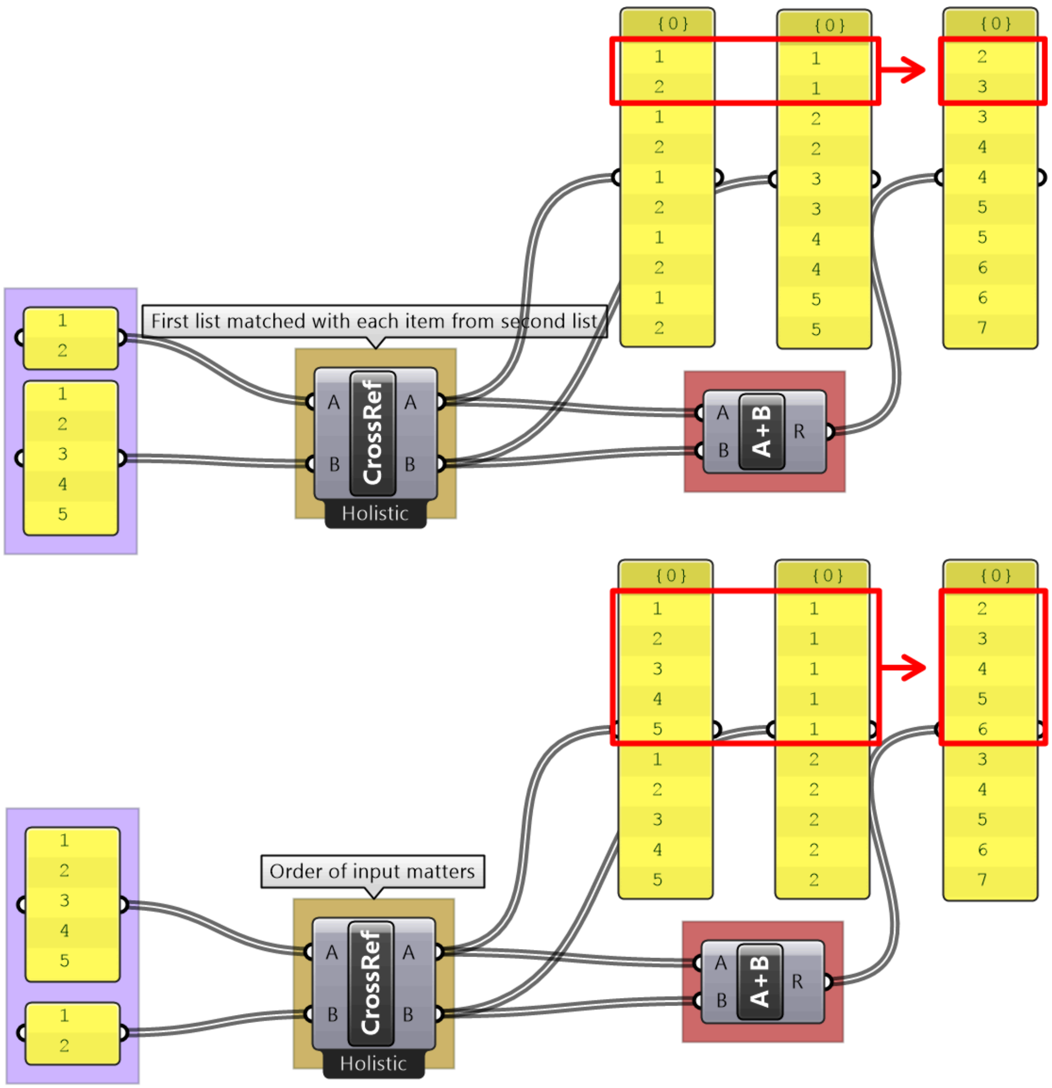


Figure (49): Cross reference matching creates longer lists to account for all possible permutations

If none of the matching methods produce the desired result, you can explicitly adjust the lists to match in length based on your requirements. For example, if you like to repeat the shorter list until it matches the length of the longer list, then you'll need to create the logic to achieve that as in the following example.

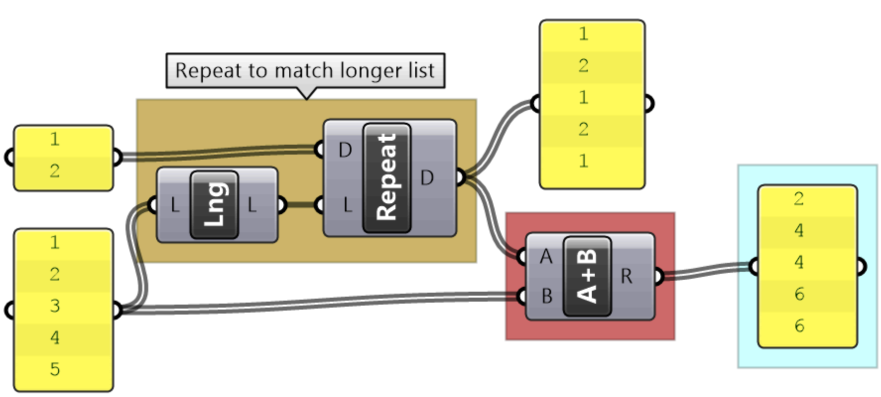
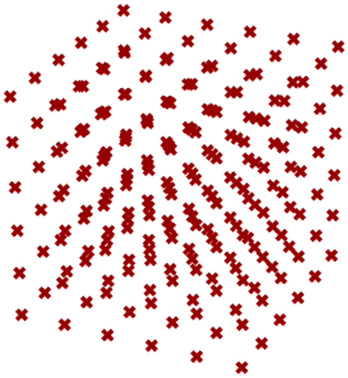
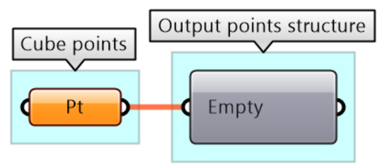
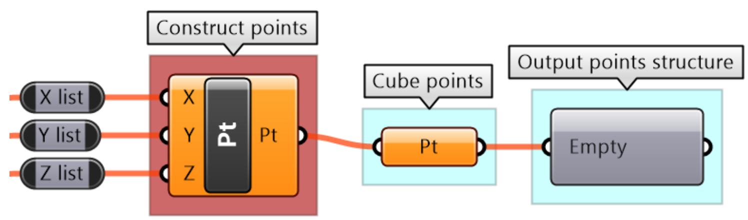
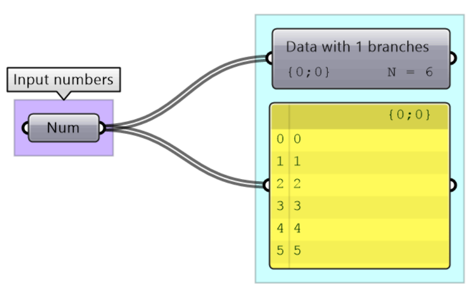
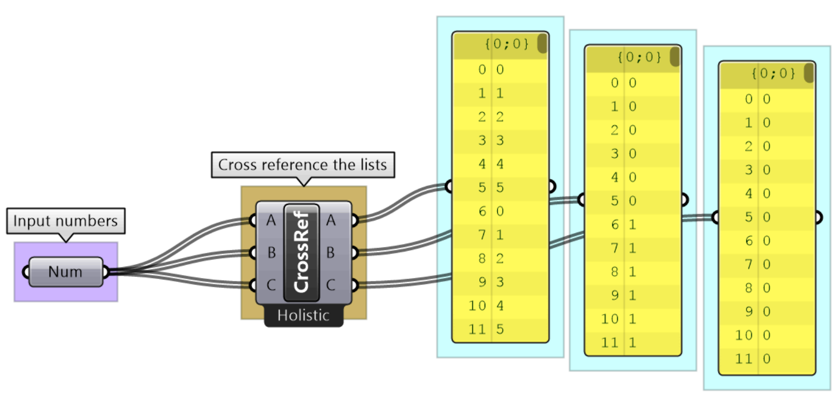


Figure (50): Need to create custom script to generate custom matching

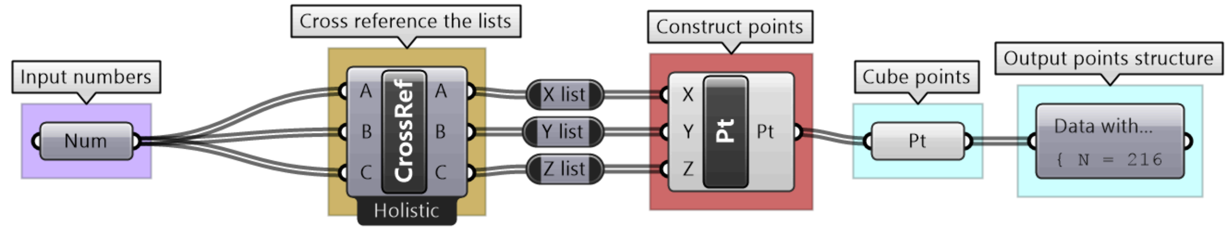
2_4_1 List matching tutorial

Use the 4-step method to generate an algorithm that takes 6 numbers (0 to 5) and turn them into a cube of points as in the image:



Solution	
Output: A list of 6x6x6 = 216 points constructed from a list of X, Y, Z coordinates	
Key process: Use the ***Construct Point*** component to generate the list of points	
Input: Examine input using the ***Parameter Viewer*** and ***Panel*** components. The given list has 6 points representing each coordinate along each axis	
Intermediate process: Need to find all possible permutations for the coordinates to create the cube of 216 points along all 3 axes Use ***Cross Reference*** matching to generate lists of coordinates that have all possible permutations	

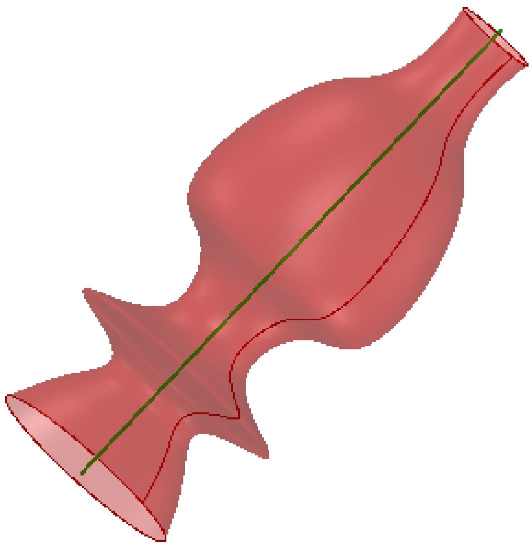
Put it all together

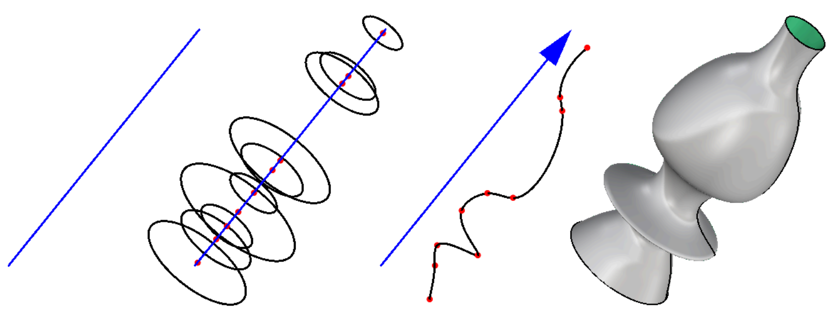
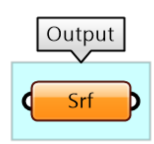


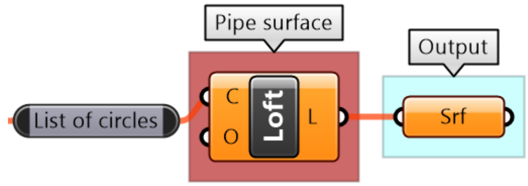
2_5: Data structures tutorials

2_5_1: Variable thickness pipe tutorial

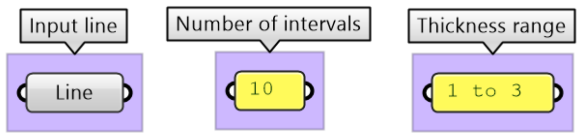
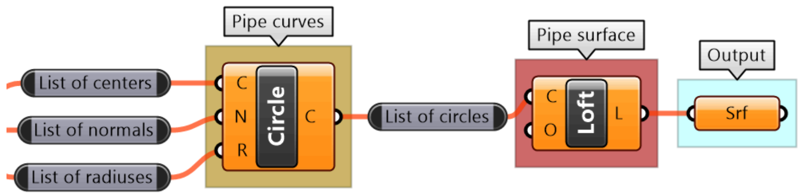
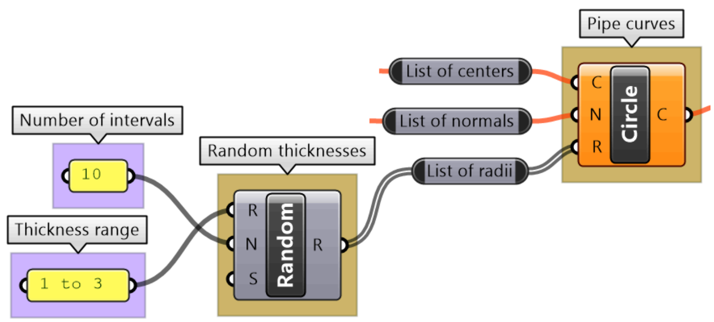
Use the 4-step method to create a surface similar to the one in the image with thickness that changes in 10 locations random along the curve. Thickness variations are random between 1 and 3 as in the image:

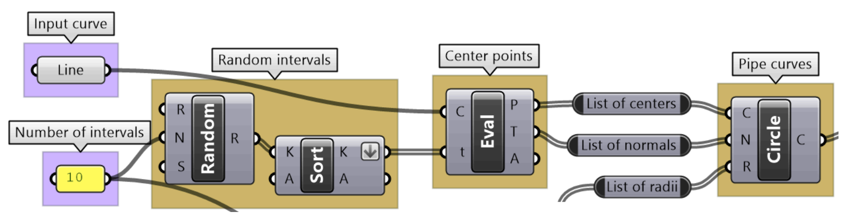


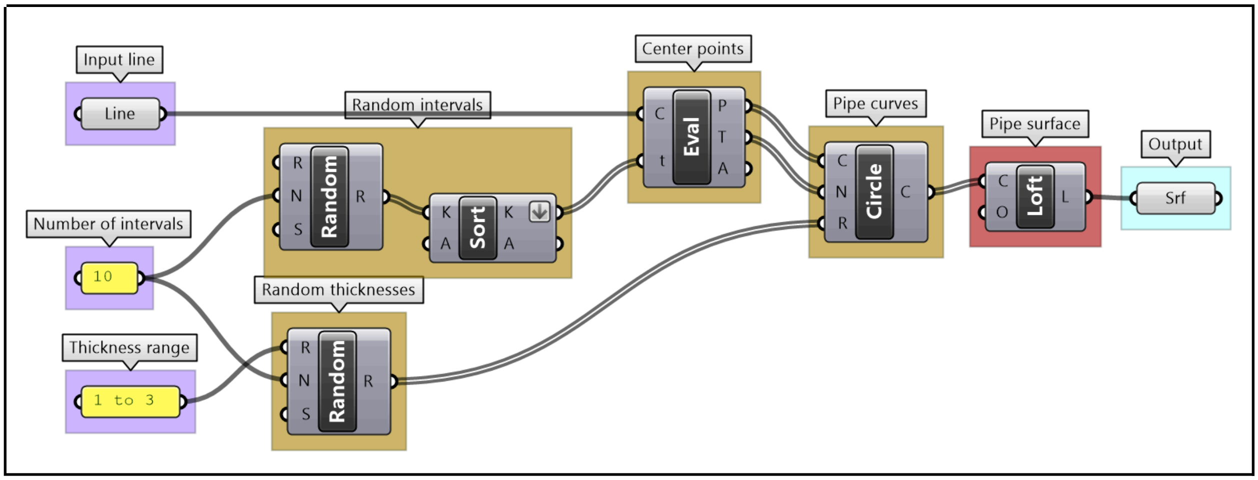
Algorithm analysis	
We can think of two different ways to generate this surface: 1. Loft circles created along a line at random locations with random radii 2. Create a profile curve at the circles start points, and Revolve around the line	
Solution steps	
Output: The surface	

<table>
<tr>
<td>Key process:
Use the Loft component to generate the surface</td>
<td>
</td>
</tr>
<tr>
<td>Input:
Line (not given, so create one)

Number of intervals (not given, assume it is equal 10)

Thickness range (not given, assume it is equal to 1.0 to 3.0)</td>
<td>
</td>
</tr>
<tr>
<td>Intermediate process #1:
The Loft is created from a list of circles. Use the Circle component that takes centers, normals and radii lists.
We can use the default Loft options.</td>
<td>
</td>
</tr>
<tr>
<td>Intermediate process #2:
To create a list of random radii, use the Random component and the input thickness range</td>
<td>
</td>
</tr>
<tr>
<td>Intermediate process #3:
Evaluate the line at random intervals. Use the Evaluate Curve component to extract center points and normals, and use the Random component to generate the parameters along the curve.

<u>Problem</u>: The loft follows the order of input curves, however the parameters (generated from the Random component) are not ordered along the line and hence it produces unordered circles.
Use the Sort List component to order the parameters before feeding them into the Evaluate Curve.</td>
<td>
</td>
</tr>
<tr>
<td colspan="2">Put it all together</td>
</tr>
</table>



2_5_2: Custom list matching tutorial

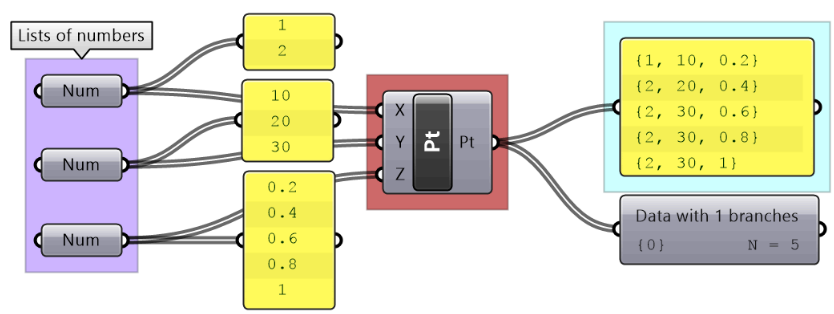
Given the following three lists of numbers: [1,2], [10,20,30] and [0.2, 0.4, 0.6, 0.9, 1], explain the default GH list matching when they are used as input. Compare the default matching with Grasshopper Shortest List matching. Finally, use the original lists to create custom matching that repeats the pattern in the shorter lists to create a periodic matching. For example [1,2] becomes [1,2,1,2,...] until it matches the length of the longer list and so on.

<table>
<tr><th colspan="2">Solution</th></tr>
<tr><td>

Construct default GH matching:

To test the matching, feed the lists into the coordinates of the ***Construct Point*** component and observe the result.

</td><td>

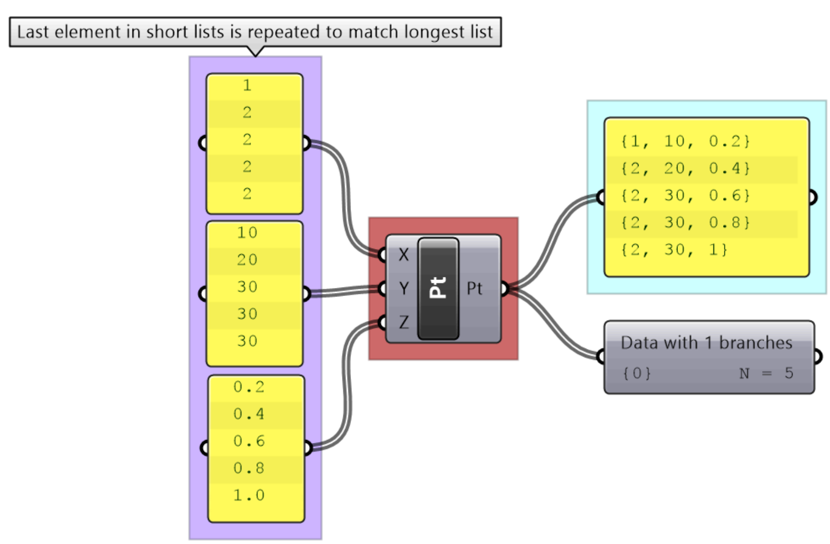


</td></tr>
<tr><td>

Analysis of GH default matching:

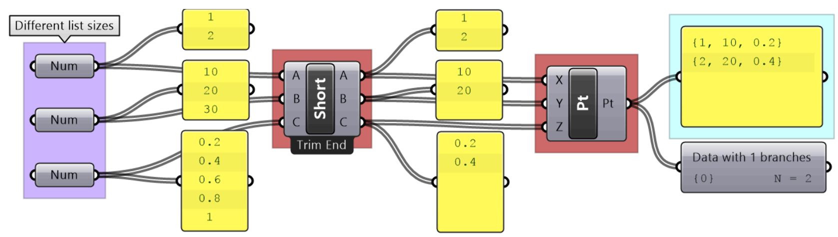
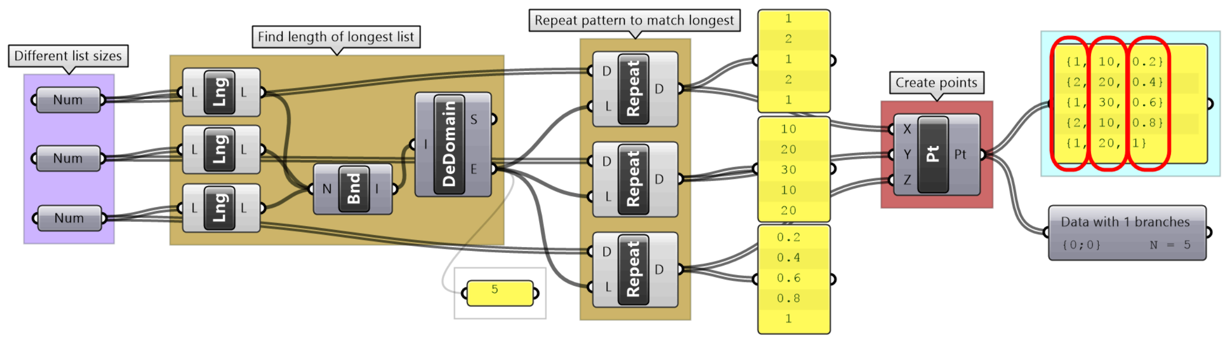
The last element of shorter lists is repeated until all lists have the same length, then elements are matched by indices

</td><td>



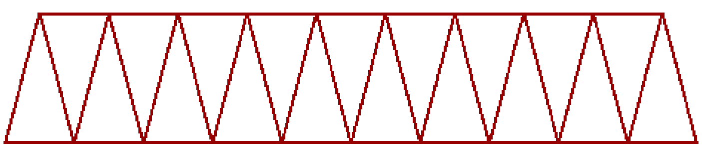
</td></tr>
</table>

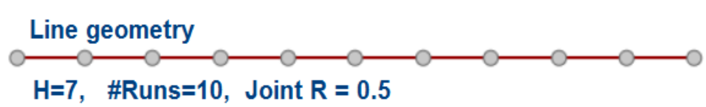
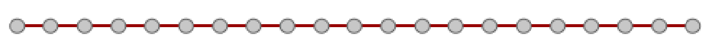
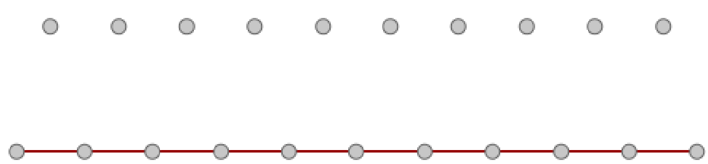
<table>
<tr>
<td>Shortest List matching:

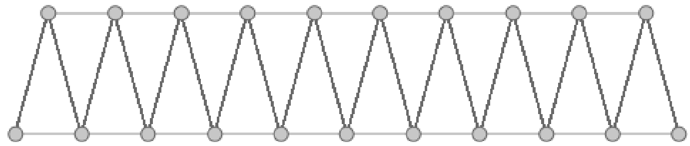
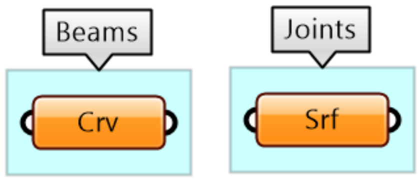
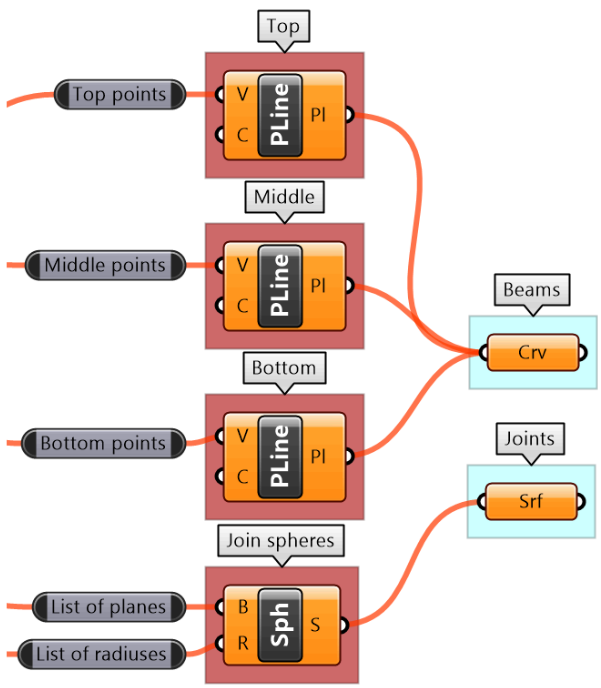
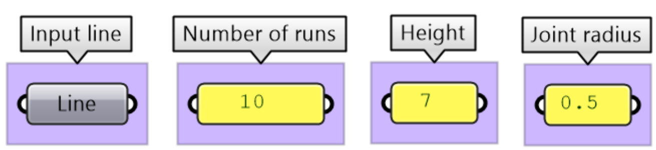
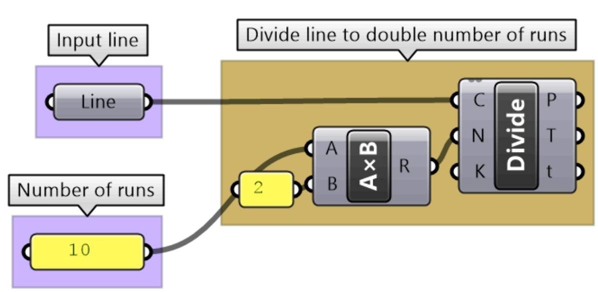
Omit additional values in longer lists so that the length of all lists equals the length of the shortest list</td>
<td>
</td>
</tr>
<tr>
<td colspan="2">Custom matching:
We know that the longest list has 5 items, but it is a good practice to make the script generic so it works with any input. First, figure out the length of the longest list, then use the Repeat component to repeat the elements in shorter lists until they match the length of the longest list.

</td>
</tr>
</table>

2_5_3: Simple truss tutorial

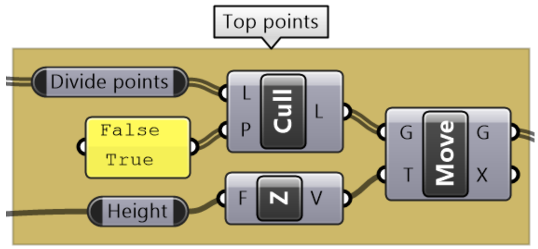
Use the 4-step method to generate a simple truss as in the image. For input, use a line (base of the truss), height, number of runs (or spans), and the radius of the joint.



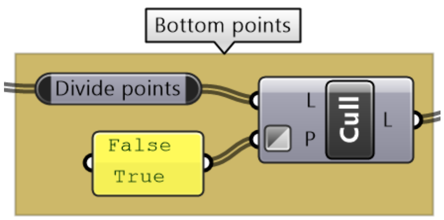
<table>
<tr><th colspan="2">Algorithm analysis:</th></tr>
<tr>
<td>Define values for the input:
L= create a Line along X-Axis
H= assume height=7
R= assume number of runs=10
J= assume joint radius=0.5</td>
<td>
</td>
</tr>
<tr>
<td>Divide the baseline into 20 spans (or 2*R)</td>
<td></td>
</tr>
<tr>
<td>Move every other point by 7 units (or H) in the Z-Axis direction</td>
<td></td>
</tr>
</table>

Create 3 sets of ordered points for the beams along the base, top and middle, then connect each of the 3 sets with a polyline. Create spheres to represent the joints.	
Solution steps:	
Output: There are 2 outputs, the beams as curves (polylines) and joints as spheres (surfaces)	
Key processes: Need to create the polylines for the top, middle, and bottom beams. Use the ***Polyline*** component with a relevant set of points for each. Use the ***Sphere*** component to create joints. Use middle points and joint radius as input.	
Input: Specify the inputs and assume values when they are not given: line, number of runs, height and joint radius	
Intermediate process #1 Divide the curve with twice the number of runs. Use ***Divide Curve*** component and ***Multiply*** the number of runs	

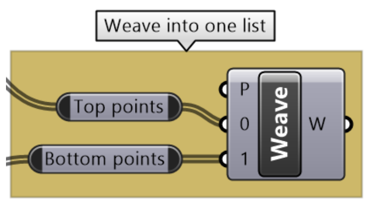
Intermediate process #2
To create top points, select every other point from the list of all divide points, then move vertically by the height amount.
Use ***Cull Pattern*** component to select points and ***Move*** component to shift vertically



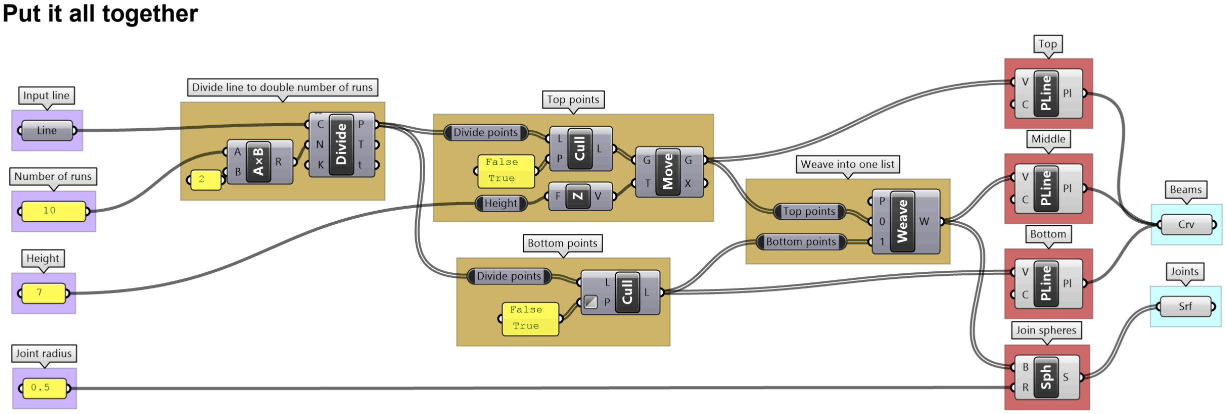
Intermediate process #3
To create bottom points, select every other point, in the invert pattern used to select top points.
Use ***Cull Pattern*** component to select points (set the ***invert*** flag for the pattern input)



Intermediate process #4
To create middle points, ***Weave*** the top and bottom points.

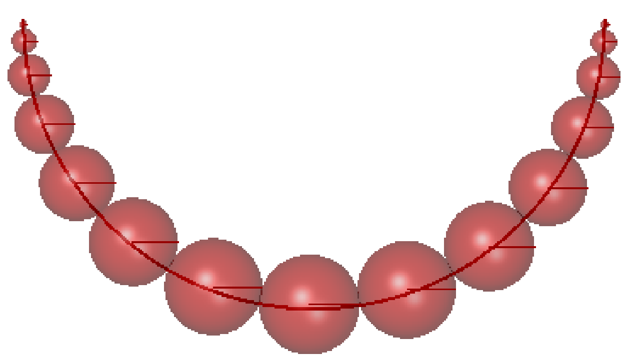


Put it all together



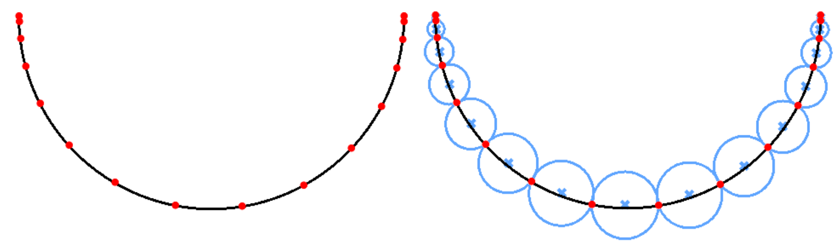
2_5_4: Pearl necklace tutorial

Create a necklace with one big pearl in the middle, and gradually smaller size pearls towards the ends as in the image. The number of pearls is between 15-25.



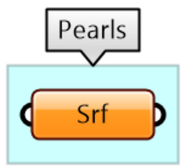
Algorithm analysis

The workflow to create the necklace follows these general lines:
1- Divide the curve into segments of variable distances (widest in the middle and narrow towards the ends).
2- Find length and midpoints of each segment
3- Create spheres at midpoints using half the length as radius

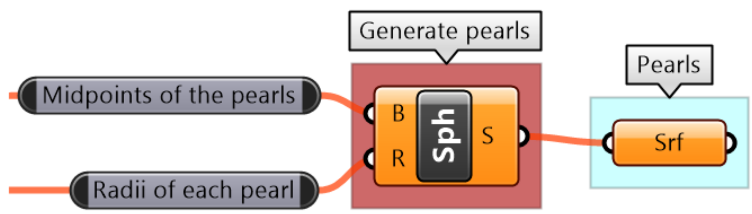


Solution steps

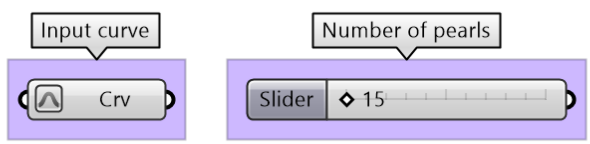
Output:
The surfaces



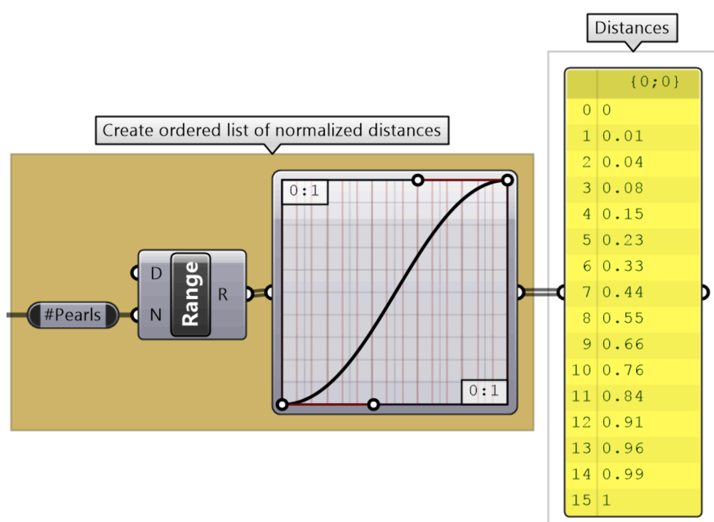
Key process:
Use the ***Sphere*** component to generate the pearl surfaces

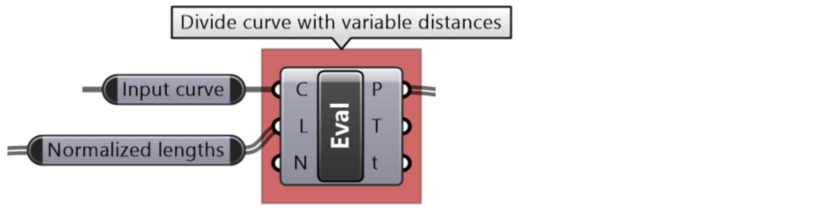


Input:
Necklace curve,
Number of pearls as a parameter (can be changed by the user)

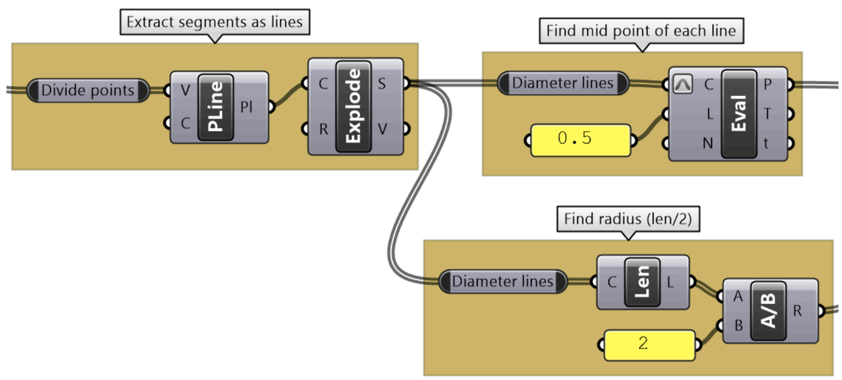
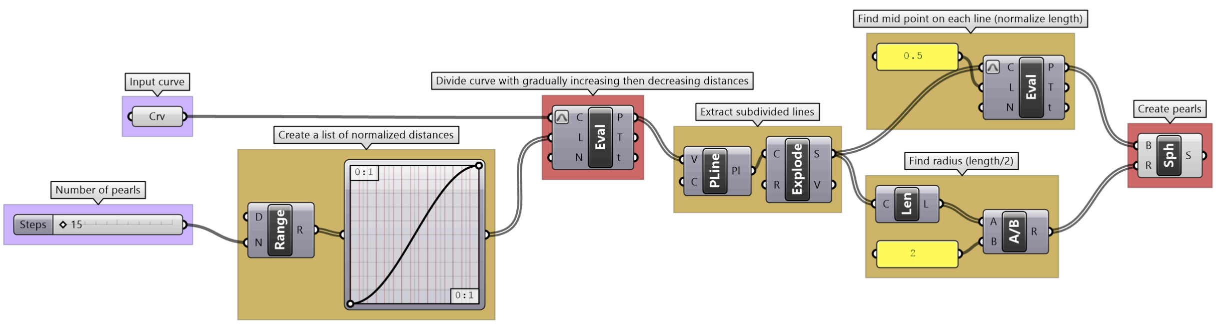


Intermediate process #1:
The ***Range*** component creates equal distances. We need to change to variable distances and for that we can use the ***Graph Mapper*** component to control the spacing.



<table>
<tr>
<td>Intermediate process #2:
Since we have normalized distances from the start of the curve (parameters are between 0 to 1), we can use the Evaluate Length component to find the divide points.</td>
<td>
</td>
</tr>
<tr>
<td>Intermediate process #3:
Generate the segments. Use Polyline and Explode components to turn the points into segments

Center points are calculated at the middle of the segments. Use Evaluate Length at mid length

Radii are calculated as half of each segment length. Use Length and Division components</td>
<td>
</td>
</tr>
<tr>
<td colspan="2">Put it all together

</td>
</tr>
</table>

Chapter Three: Advanced Data Structures

This chapter is devoted to the advanced data structure in GH, namely the data trees, and different ways to generate and manage them. The aim is to start to appreciate when and how to use tree structures, and best practices to effectively use and manipulate them.

3_1: The Grasshopper data structure

3_1_1 Introduction

In programming, there are many data structures to govern how data is stored and accessed. The most common data structures are variables, arrays, and nested arrays. There are other data structures that are optimized for specific purposes such as data sorting or mining. In Grasshopper, there is only one structure to store data, and that is the **data tree**. Hold on, what about what we have learned so far: **single** item and **list** of items? Well, in GH, those are nothing but simple trees. A single item is a tree with one branch that has one element, and a list is a tree with one branch that has a number of elements. It is actually pretty elegant to be able to fit all data in one unifying data structure, but at the same time, this requires the user to be aware and vigilant about how their data structure changes between operations, and how that can affect intended results. This chapter attempts to demystify the data tree of Grasshopper.

3_1_2 Processing data trees

We used the ***Panel*** and ***Parameter Viewer*** components to view the data structure. We will use both extensively to show how data is stored. Let's start with a single item input. The ***Parameter Viewer*** has two display modes, one with text and one that is graphical. You can see that the single item input is stored in one branch that has only one item.

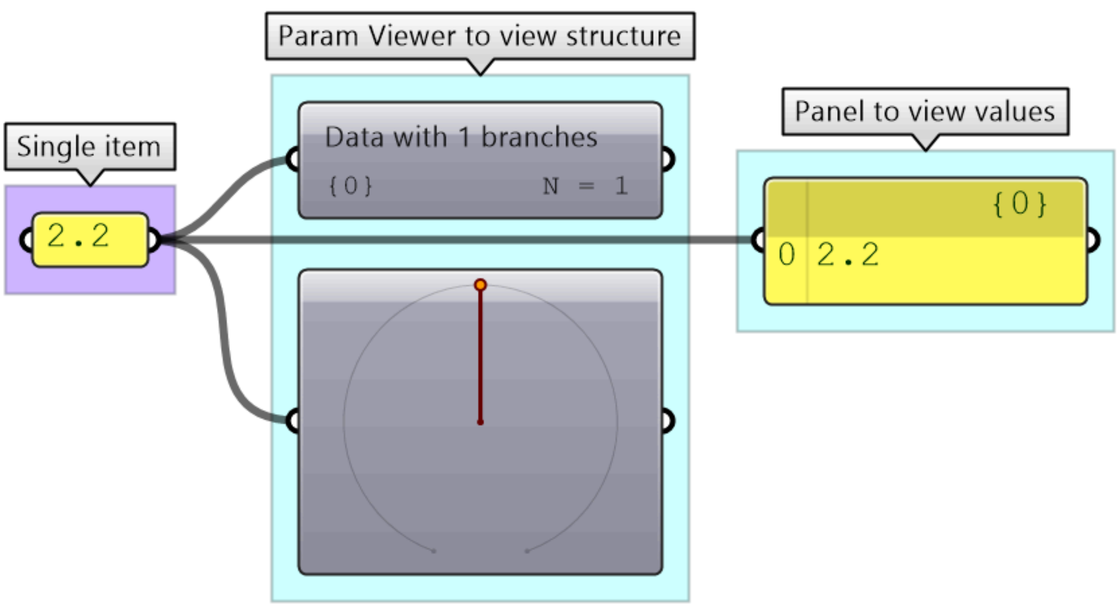


Figure (51): Different ways to preview the data structure in Grasshopper

The ***Parameter Viewer*** shows each branch address (called “Path”), and the number of elements in that branch as shown in Figure (52).

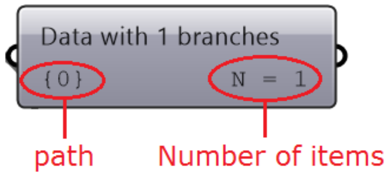


Figure (52): The ***Parameter Viewer*** indicates the path address and the number of elements in each branch

A list of items is typically stored in a tree with one branch. Figure (53). However, the three items can also be stored in three different branches. Figure (54).

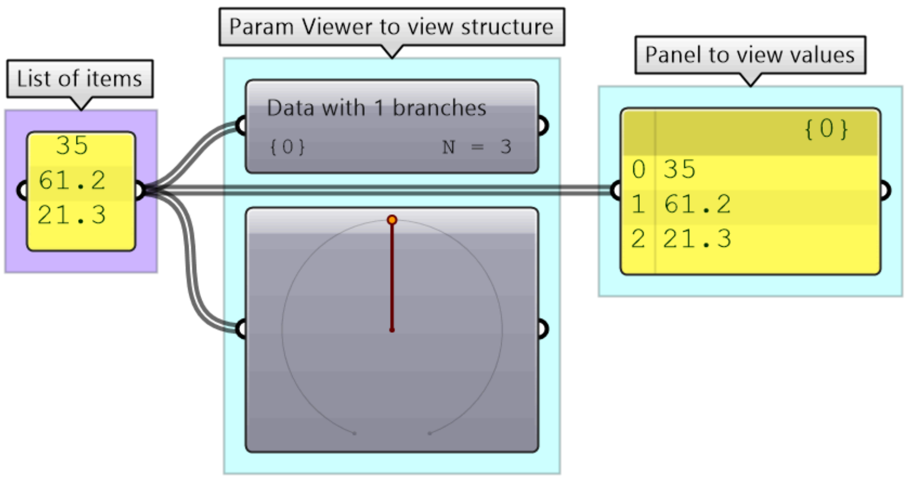


Figure (53): A list is a tree that has one branch with multiple elements

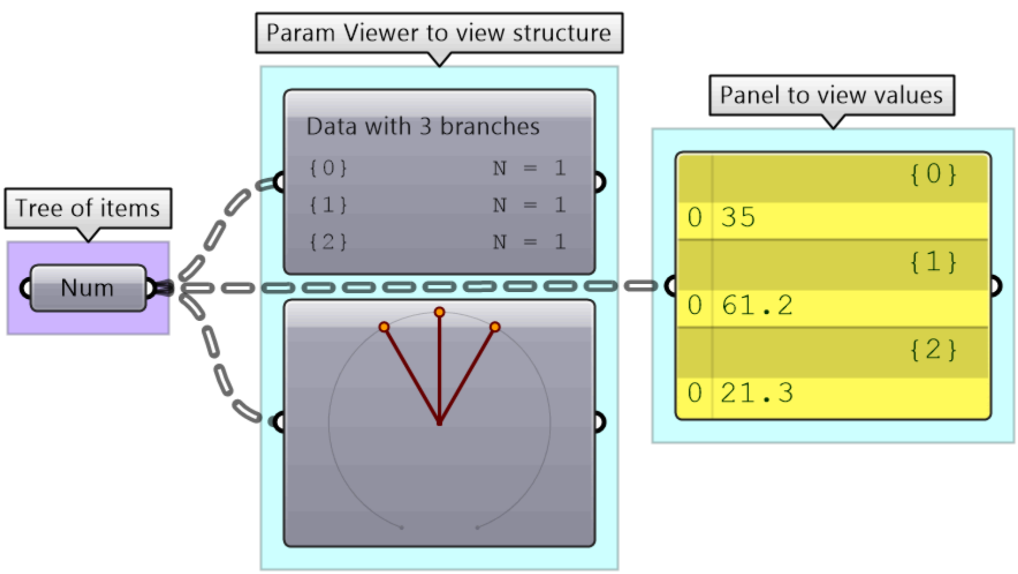


Figure (54): A tree contains any number of branches with any number of elements in each branch

The key to understanding the Grasshopper data structure is to be able to answer the following question: **What is the significance of storing x number of values in one branch vs using x number of branches to store one value in each branch?**

The data structure informs GH components about how to match input values. In other words, components may process data differently based on their structure. The following example illustrates how different data structures for the same set of values can affect the result.

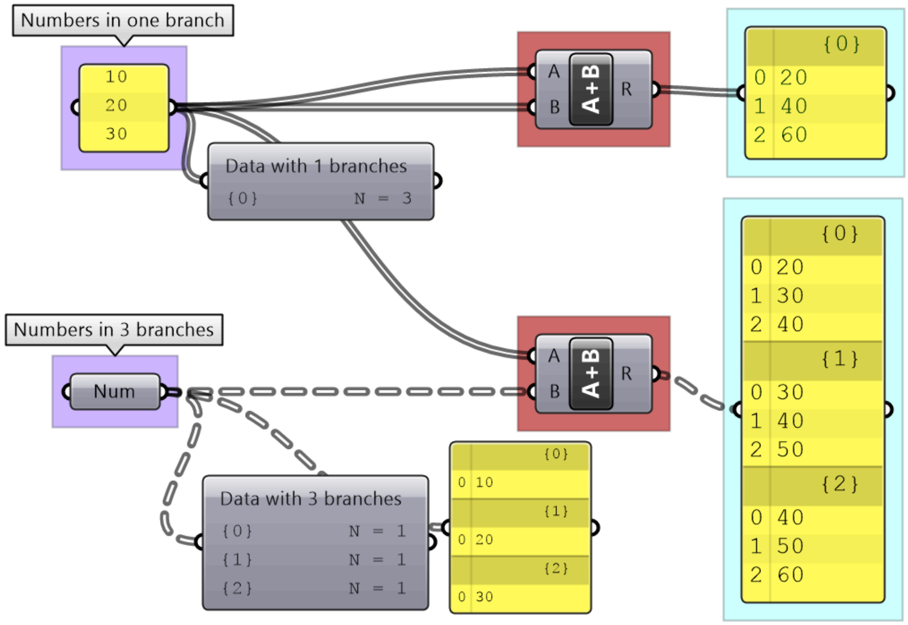


Figure (55): Organizing same set of value in different data structures affect the output

We will elaborate on data tree matching later, but you can already see that GH components do pay attention to the data structure and the result can vary considerably based on it. This is one of the complications inherited in using one unifying data structure in a programming language.

3_1_3 Data tree notation

The first step to understanding data trees is to learn the GH notation of trees. As we have seen from the examples, trees consist of branches, and each branch holds a number of elements. The address or path of each branch is represented with integers separated by semicolons and enclosed in curly brackets. The index of each element is enclosed by square brackets. This diagram shows a breakdown of the address of elements in trees.

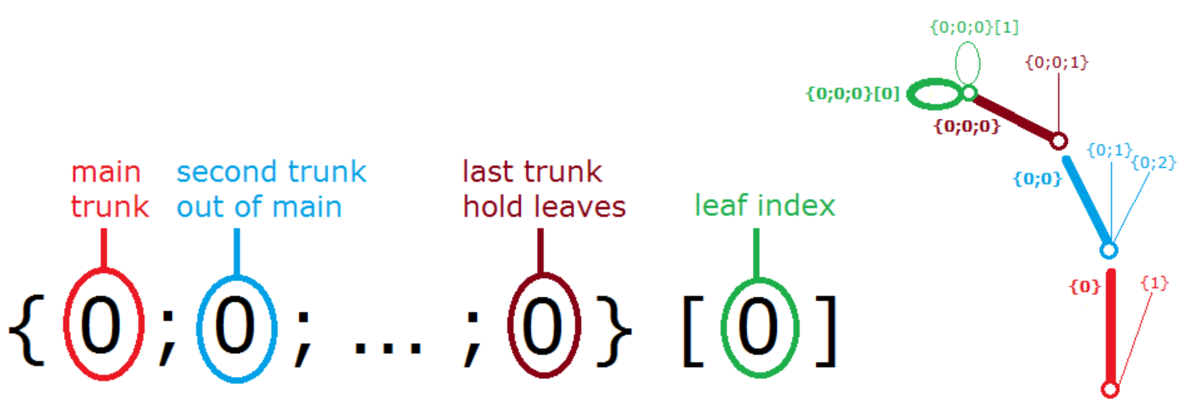


Figure (56): Address of elements include the address of the branch and the index of the element in the branch

Here are a few examples of various tree structures and how they show in the ***Parameter Viewer*** and the ***Panel***.

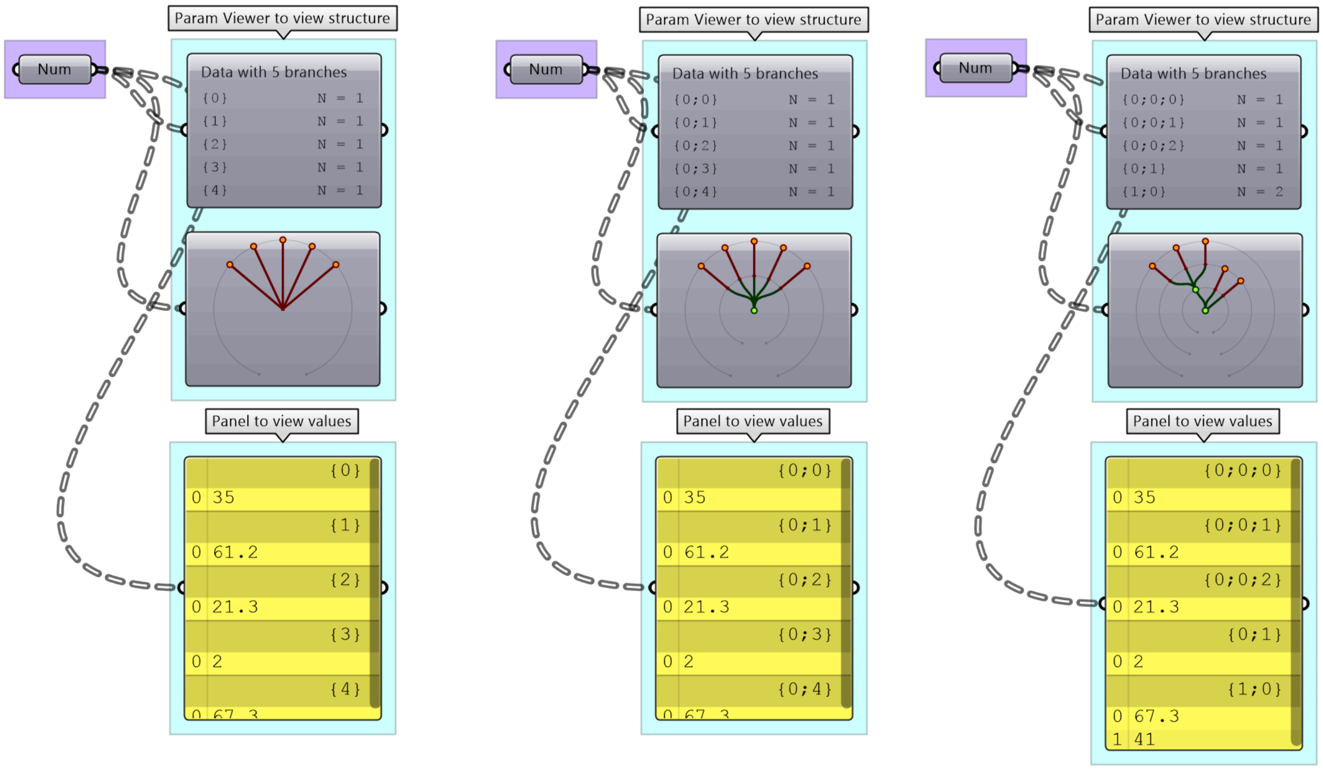
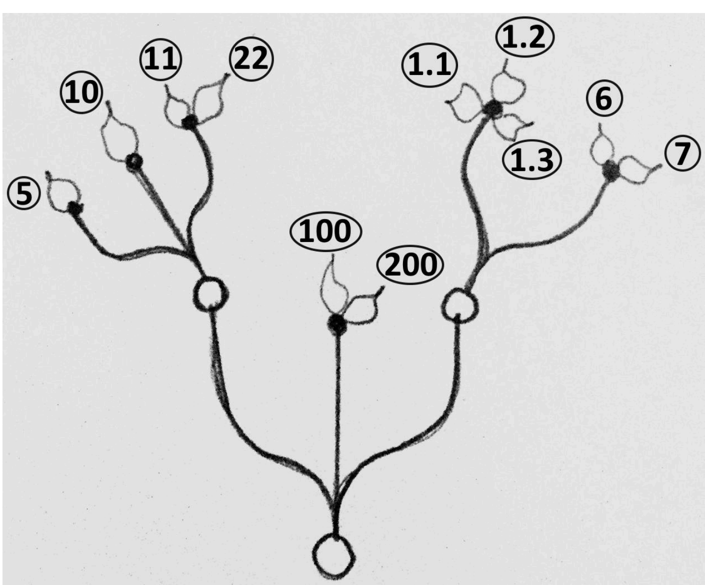
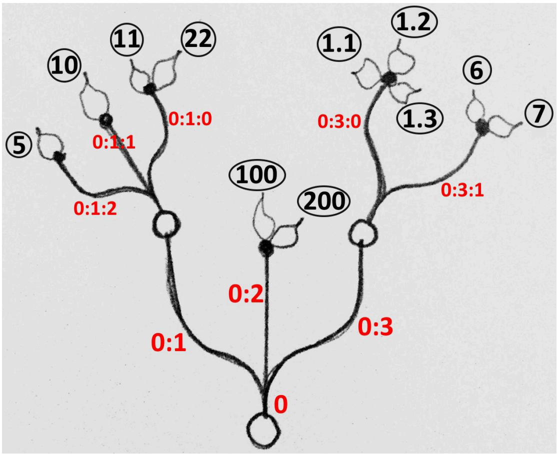
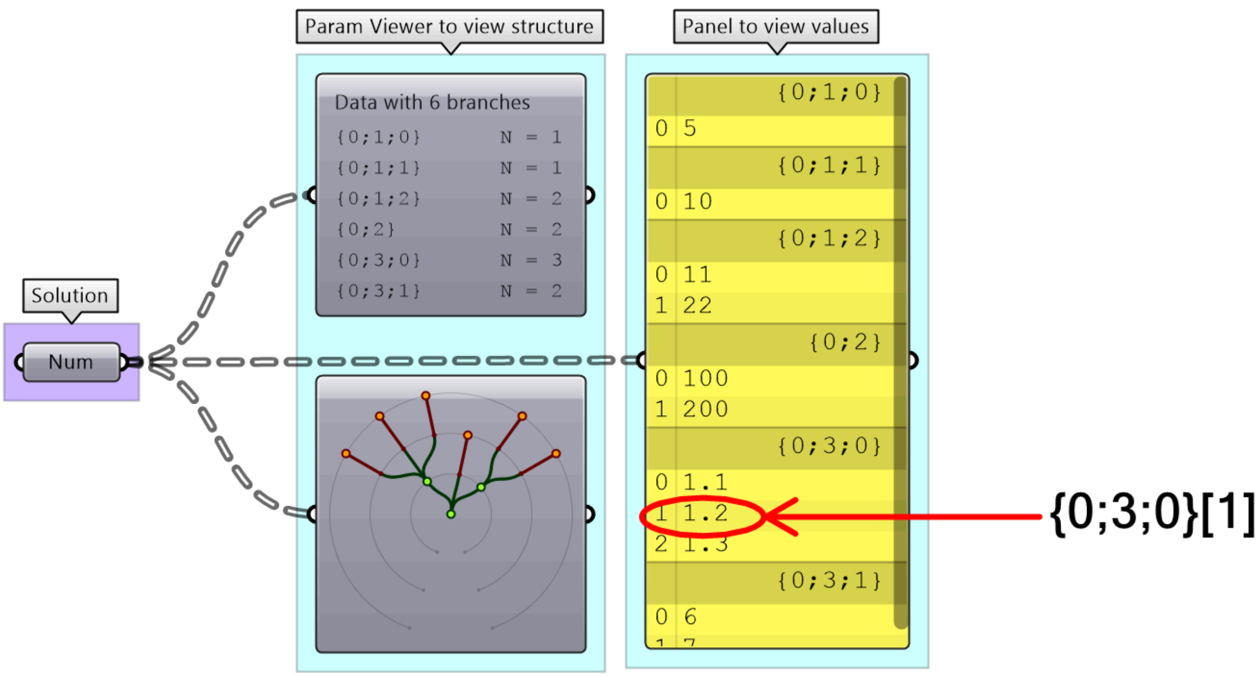


Figure (57): Same set of values held in different structures.
Left: 5 trunks (5 trees) with one item in each. Middle: 5 branches out of one trunk (1 tree), and each branch holds a single item. Right: two trunks (2 trees), the first has 2 branches with the first branching into 3 branches, each holds one item, the second holds 1 item. The second trunk holds 2 items.

3_1_1 Data tree tutorial:

Construct a tree of numbers shown in the image using the ***Number*** parameter only.
What is the full address to the item "1.2" ? Note that order of branches and leaves is always from left to right going clockwise



Solution	
	The path for“**1.2**” is: **{ 0 ; 3 ; 0} [1]** Note: The three branches from the main trunk are set here to 0:1, 0:2, and 0:3. They also could have been 0:0, 0:1 and 0:2. Both are correct.
	

3_2: Generating trees

There are many ways to generate complex data trees. Some explicit, but mostly as a result of some processes, and this is why you need to always be aware of the data structures of output before using it as input downstream. It is possible to enter the data and set the data structure directly inside any Grasshopper parameter. Once set, it is relatively hard to change and therefore is best suited for a constant input. The following is an example of how to set a data tree directly inside a parameter.

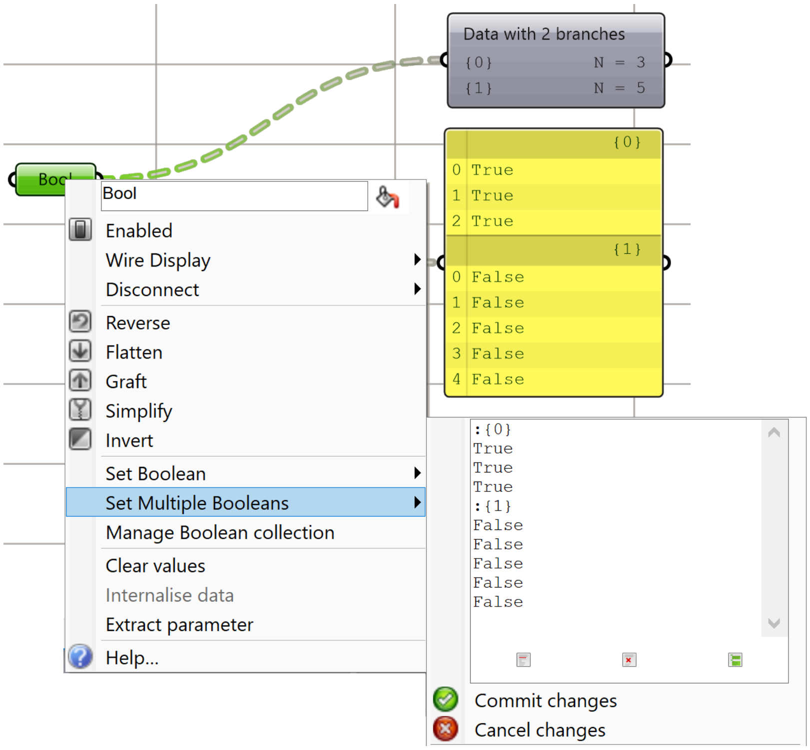
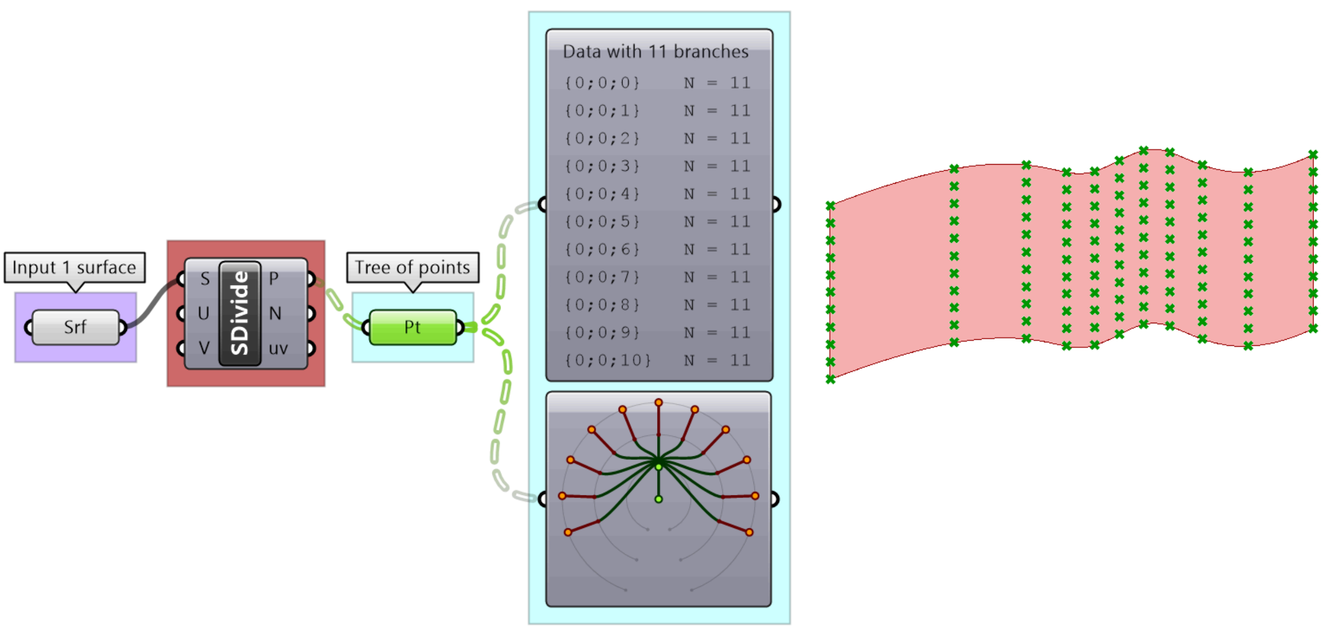


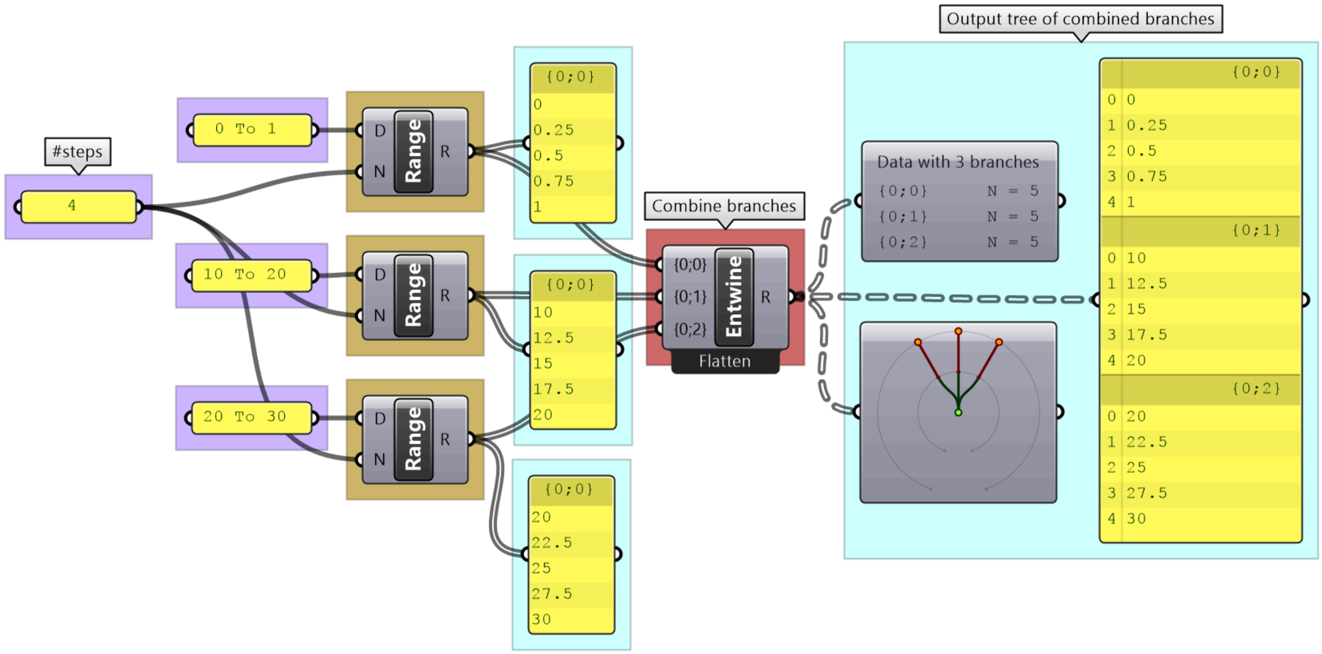
Figure (58): Set data trees directly inside the parameter

There are many components that generate data trees such as ***Grid*** and ***DivideSrf***, and others that combine lists into a tree structure such as ***Entwine***. Also all the components that produce lists can also create a tree if the input is a list. For example, if you input more than one curve into the ***DivideCrv*** component, we get a tree of points.



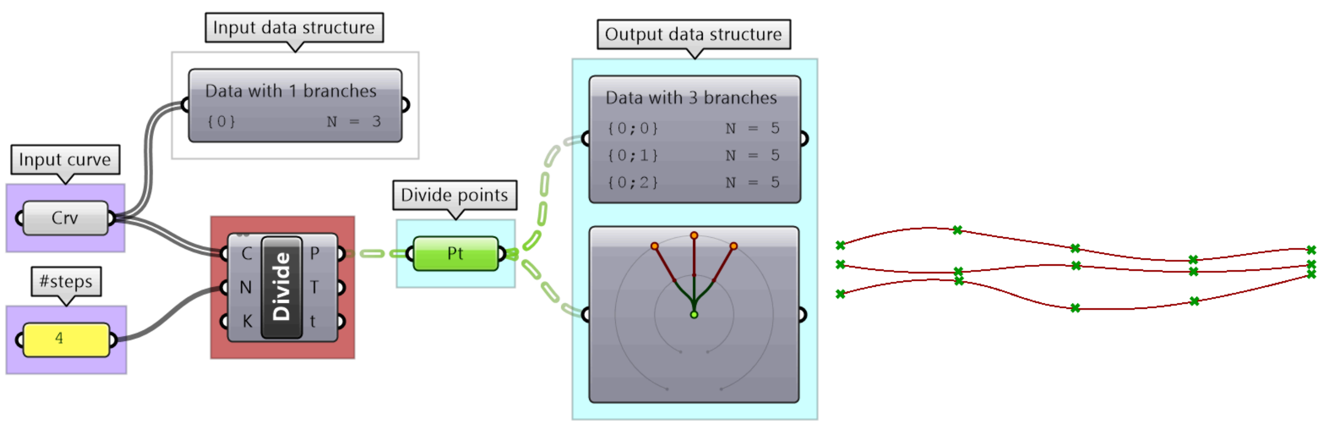
Figure(59): The ***SDivide*** component takes one input (surface) and outputs a data tree (grid).

All components that generate lists of numbers (such as ***Range*** and ***Series***) can also generate trees when given a list of input.



Figure(60): ***Entwine*** component takes any number of lists and combines them into a tree structure.

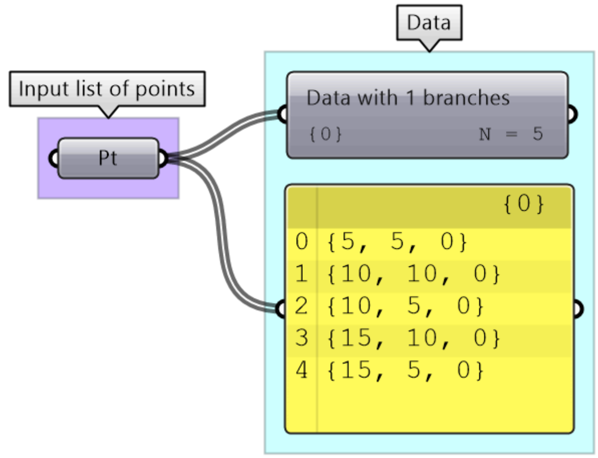
Perhaps one of the most common cases to generate a tree is when dividing a list of curves to generate a grid of points. So the input is one list and the output is a tree.



Figure(61): ***Divide*** component takes any list (curves) and generates a tree structure (grid).

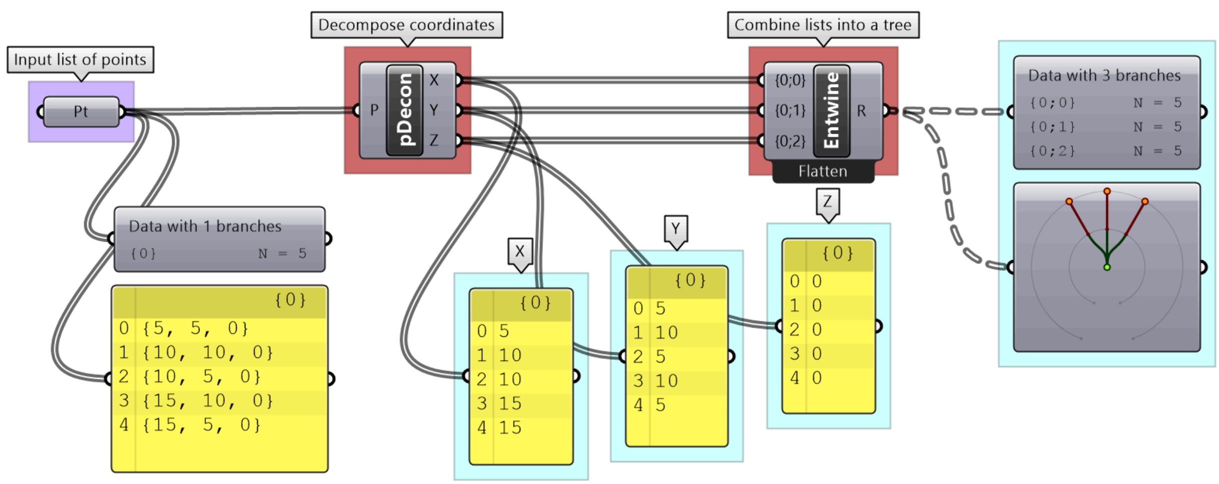
3-2-1 Generating trees tutorial

Given the following list of points, construct a number tree with 3 branches, one for each coordinate.



Solution

Discussion:
Each input point is a single data item that contains 3 numbers (coordinates). We know we would like to isolate each coordinate into a separate list, then combine them into one data structure. Hence we need to first deconstruct input points (use ***Deconstruct*** of ***pDecon*** component), then combine the lists into one structure (use ***Entwine*** component).

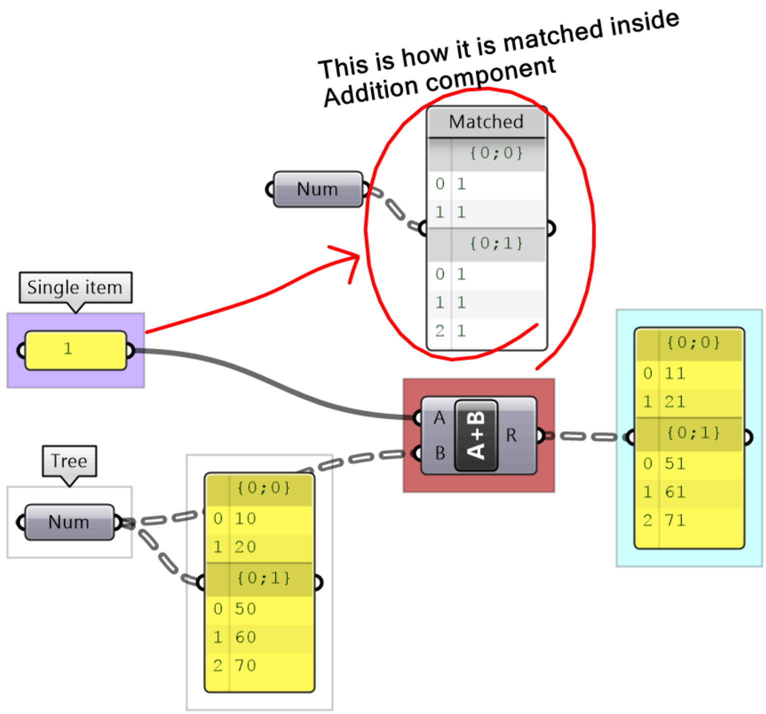


3_3: Tree matching

We explained the ***Long***, ***Short*** and ***Cross*** matching with lists. Trees follow similar conventions to expand the shorter branches by repeating the last element to match. If one tree has fewer branches, the last branch is repeated. The following illustrates common tree matching cases.

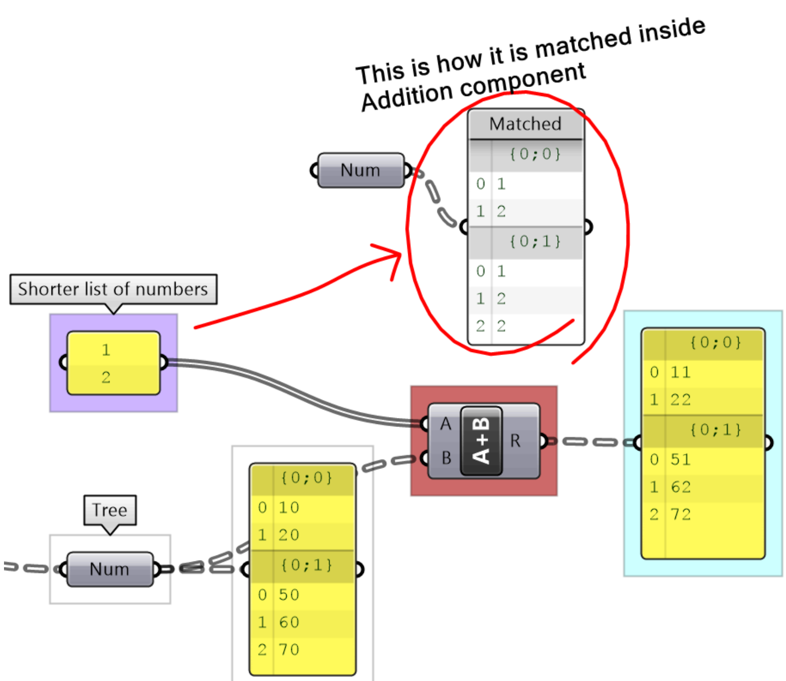
3_3_1: Item-to-tree matching

When matching an item to a tree, a matching tree structure is created and the item is repeated. For example when adding a single number to a tree of numbers, the single number is added to every item in the tree and the result is a tree with matching structure to the input tree.



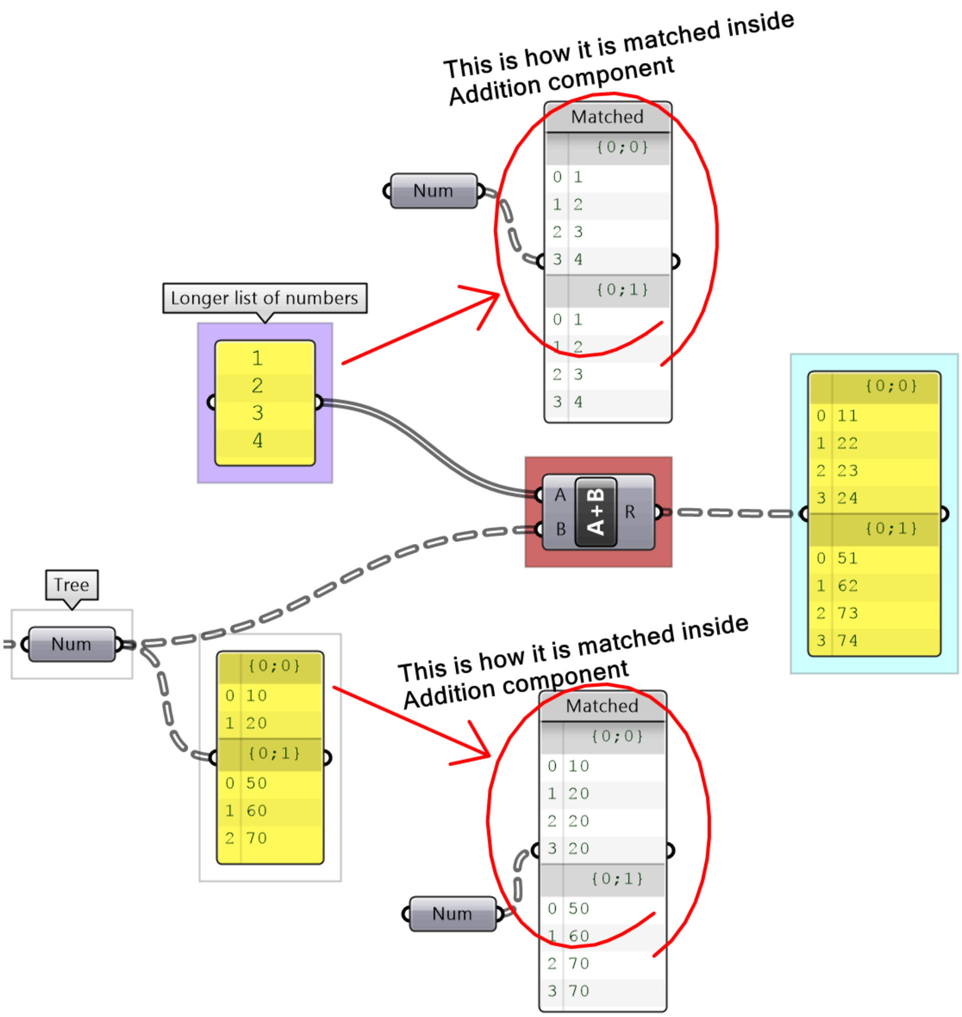
3_3_2: Short-list-to-tree matching

When matching a short list to a tree, where the length of the list is shorter than the tree branches, a matching tree structure is created where the list is repeated in each branch, and the last item in the short list is repeated. See the following example adding a list of two number to a tree of numbers.



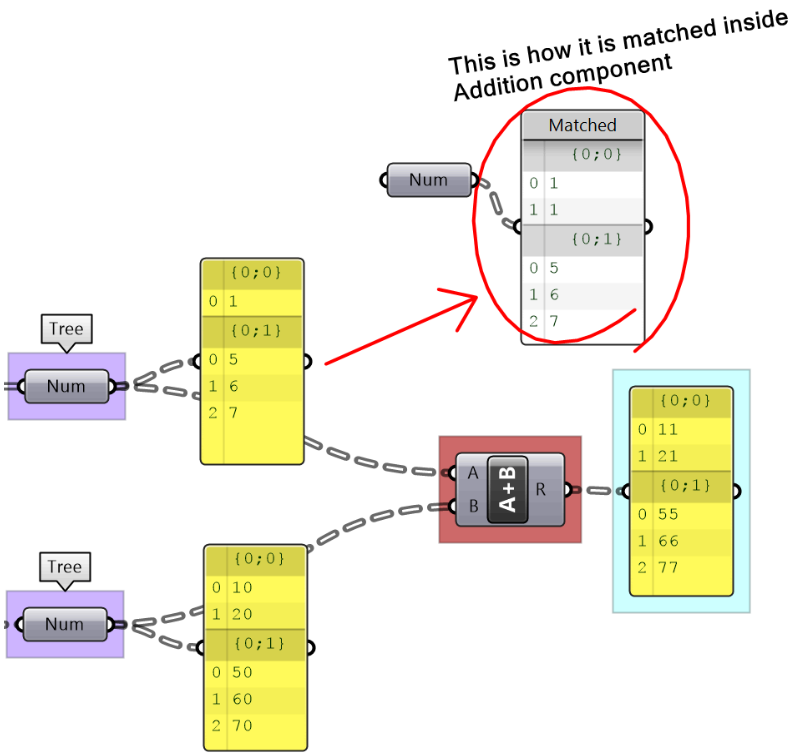
3_3_3: Long-list-to-tree matching

When matching a long list to a tree with branches that are shorter than the list, the tree branches expand to match the length of the list. The last item in each branch is repeated to match the list length Note that the resulting tree structure will be different than the input tree. In the following example, both input, the list and the tree, are modified to arrive at a matching structure, then the addition result has a new data structure.

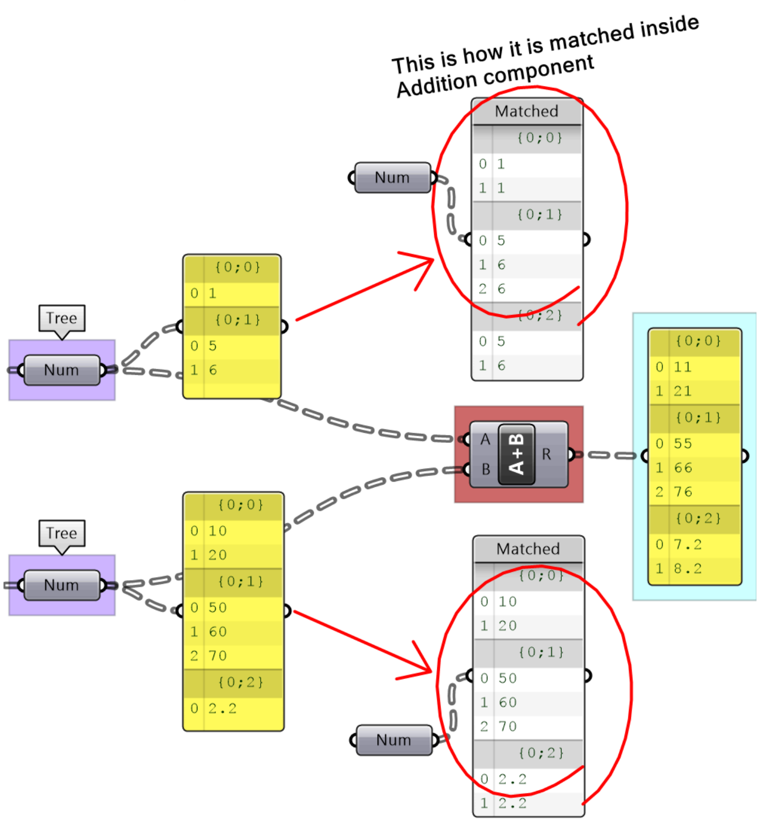


3_3_4: Tree-to-tree matching

There are numerous possibilities when matching two trees, but the basic principle applies. The goal is to find a tree structure that can combine both input tree structures. Let's assume the case when there is a simple tree with one level of branches that match in depth. There are two possibilities. The first is that both input trees have the same number of branches. In this case, the length of the shorter corresponding branches is matched. The output tree might end up matching at least one of the input trees, or be different to both.



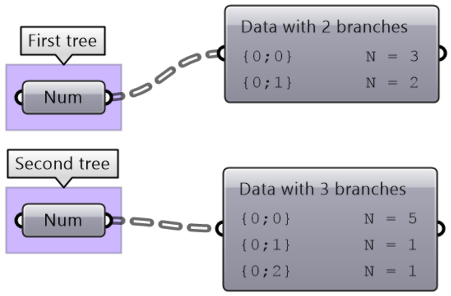
The second possibility is that one tree might have more branches than the other. In that case, new branches are inserted into the smaller tree repeating the last branch, then each branch is expanded (repeating the last item in the branch) to create matching length among all corresponding branches as in the following example.



When working with trees, it is of utmost importance to examine the data structure of each input before using it as input to one component. A small change in the structure can have a big impact.

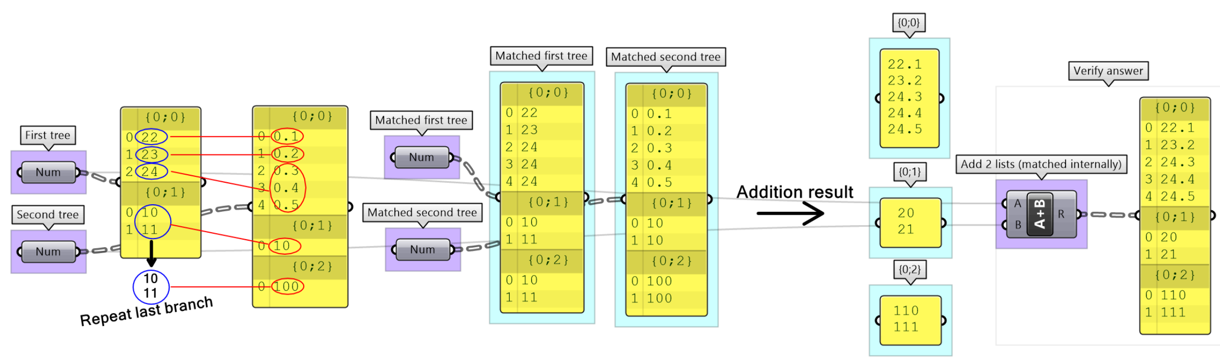
3_3_1 Tree matching tutorials

Inspect the following 2 number structures, then predict the structure and result of adding them (with default Grasshopper matching). Verify your answer using the ***Addition*** components.



Solution

Key solution idea: The two input trees have different number of branches and different number of elements in each branch. The last branch of the shorter tree is repeated to match the number of branches, then corresponding branches are matched by repeating the last element of the shorter branch.



3_4: Traversing trees

Grasshopper provides components to help extract branches and items from trees. If you have the path to a branch or to an item, then you can use ***Branch*** and ***Item*** components. You need to check the structure of your input so you can supply the correct path.

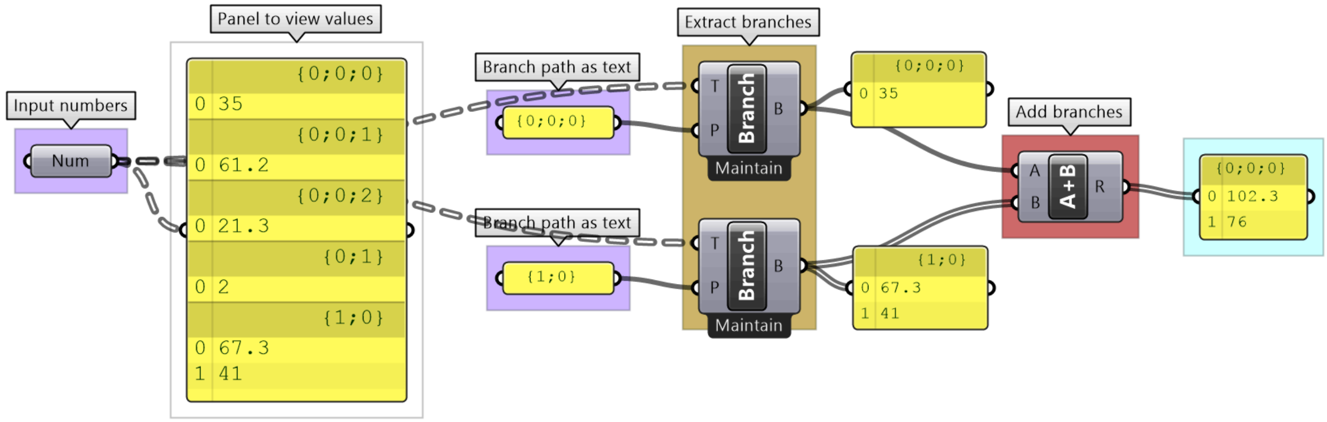


Figure (62): Select branches from a tree

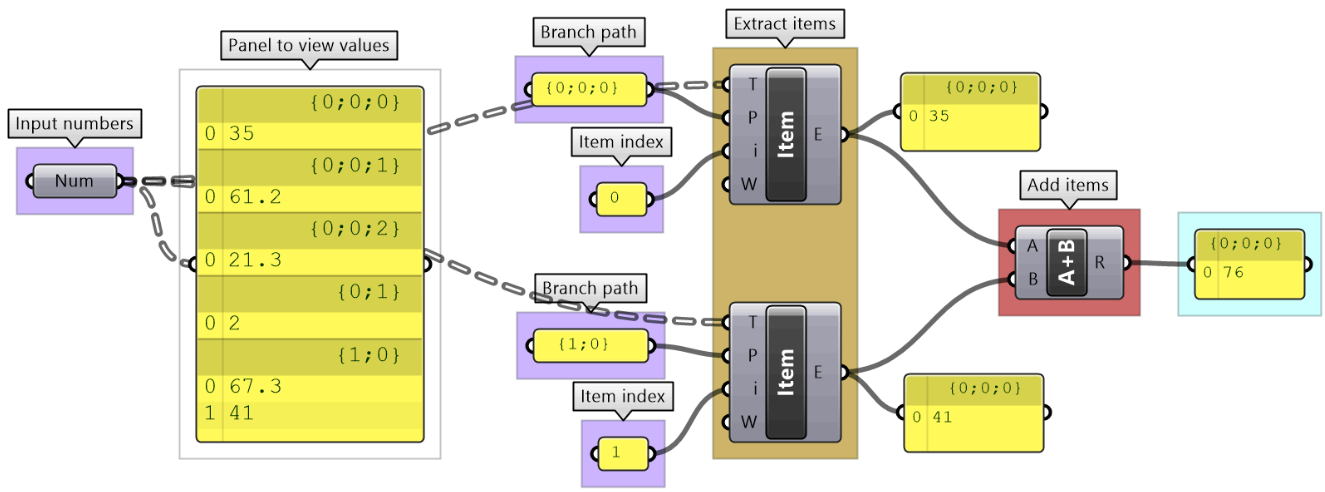


Figure (63): Select items from a tree

If you know that your structure might change, or you simply do not want to type the path, you can extract the path using the ***Param Viewer*** and ***List Item*** components.

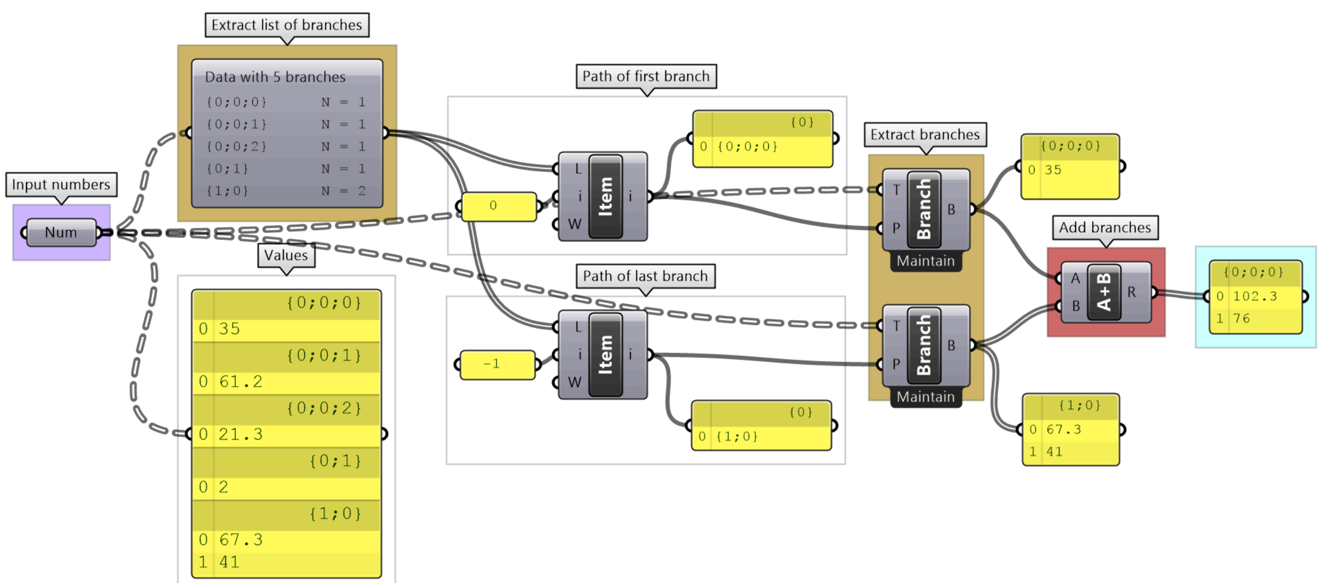
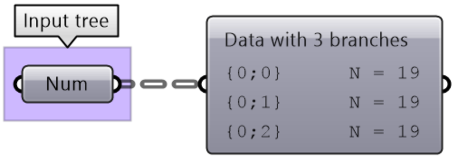


Figure (64): Example of how to extract data paths dynamically

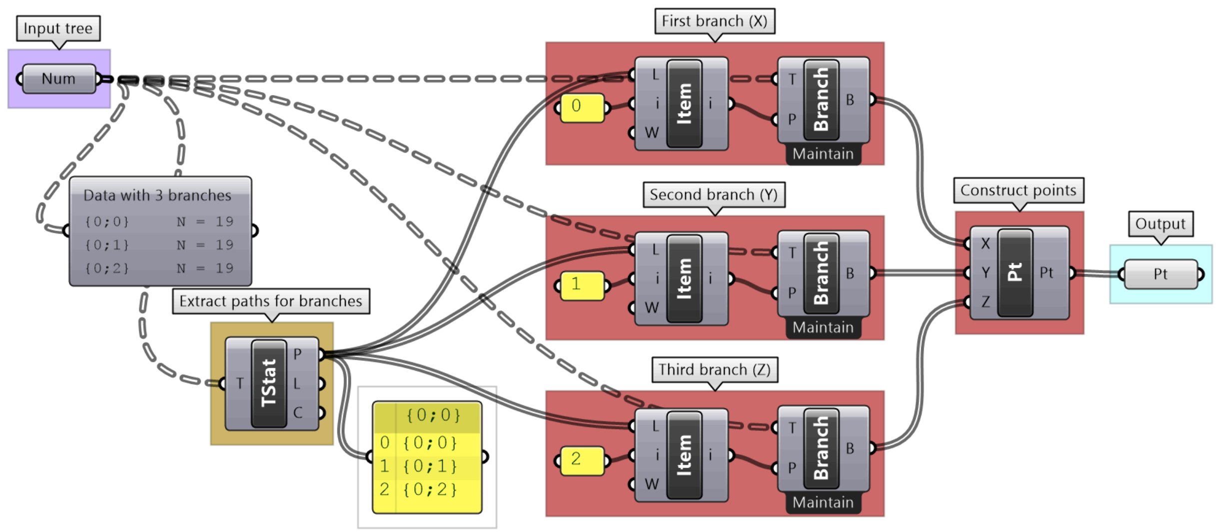
3_4_1 Traversing trees tutorial

The following tree has 3 branches for each one of the coordinates (x, y, z) of some list of points. Use that tree to construct a list of these points.



Solution

Key solution idea: We can construct a point list using as input 3 lists representing X, Y and Z values. If we can isolate the 3 branches of the input tree, then we will be able to feed them to the point construction component.



3_5: Basic tree operations

Basic tree operations are widely used and you will likely need them in most solutions. It is very important to understand what these operations do, and how they affect the output.

3_5_1: Viewing the tree structure

As we have seen in the data matching, different data structures of the same set of elements produce different results. Grasshopper offers three ways to view the data structure, the ***Parameter Viewer*** in text or diagram format, and the ***Panel***.

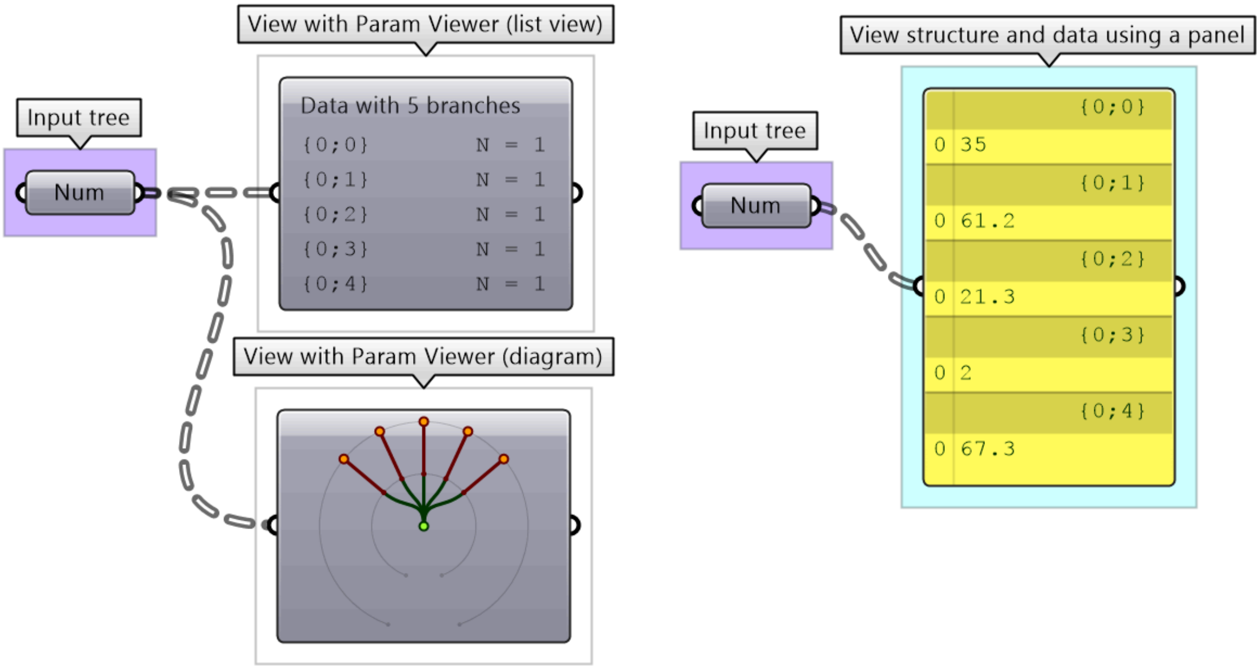


Figure (65): View trees using the ***Parameter Viewer*** and the ***Panel*** components

Tree information can be extracted using the **TStats** component. You can extract the list of paths to all branches, number of elements in each branch and the number of branches.

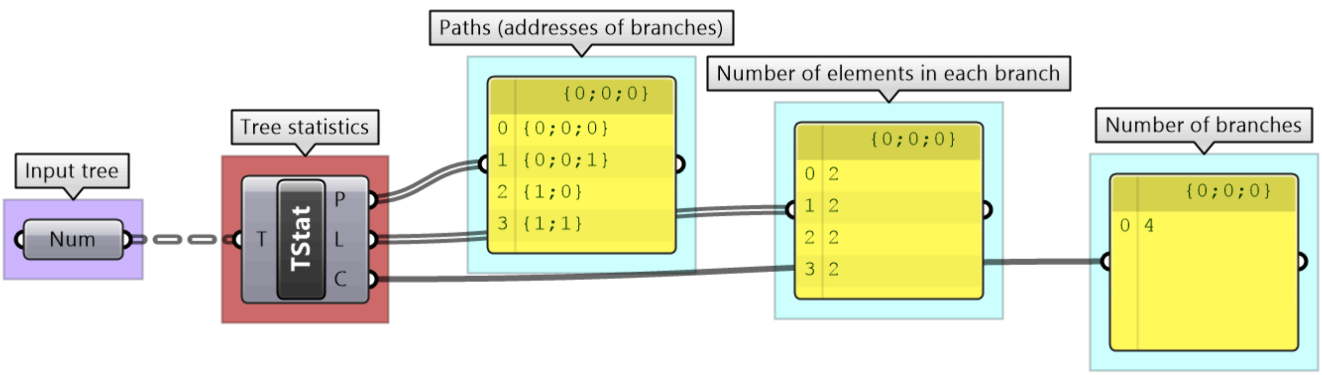
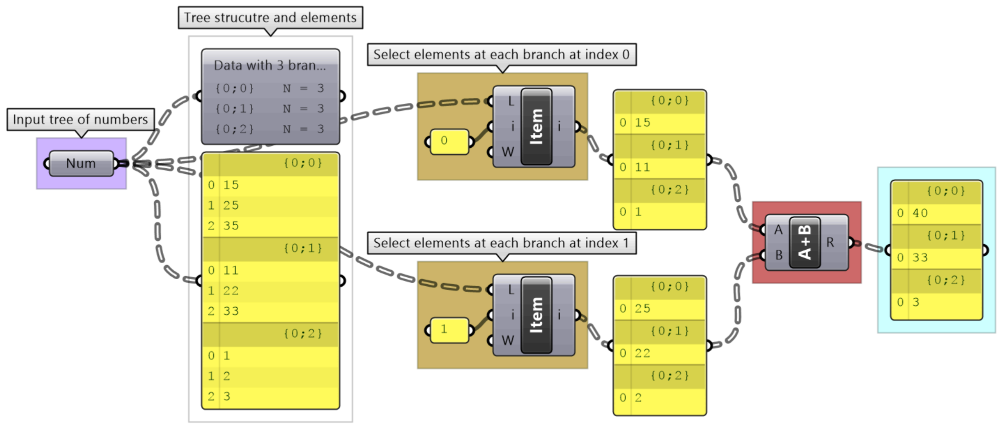
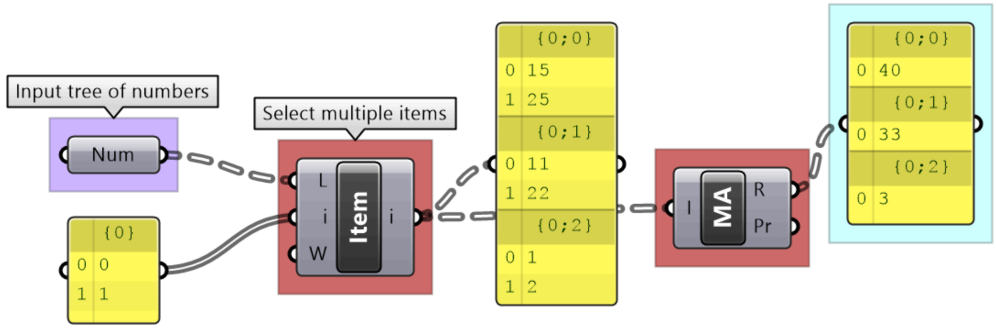
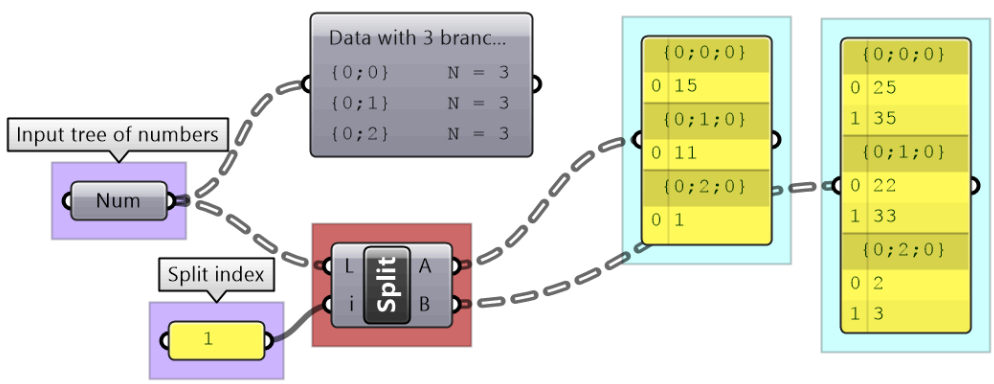
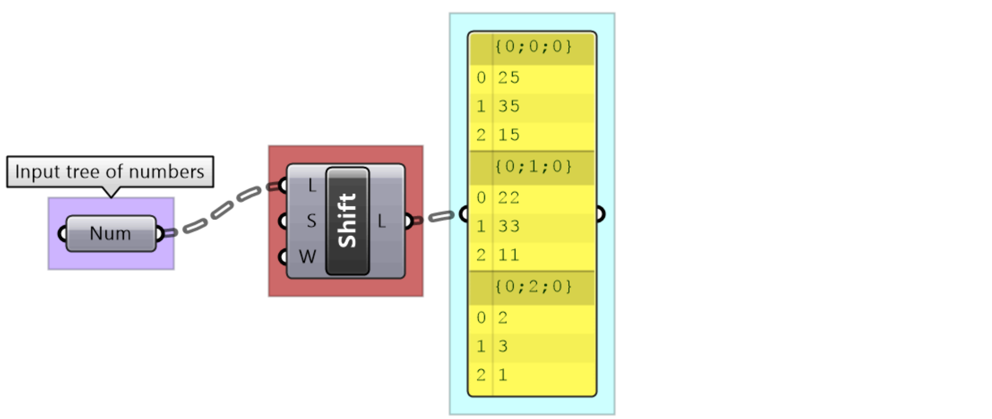


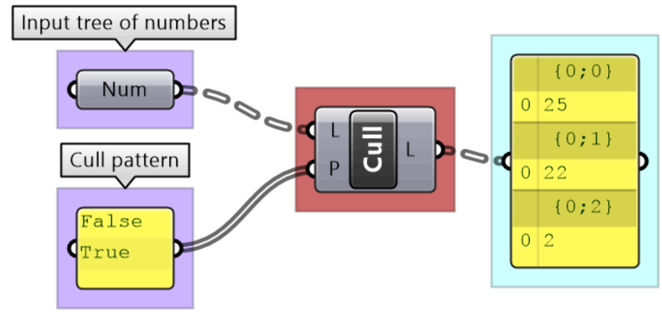
Figure (66): Extract trees structure using ***TStats*** component

3_5_2: List operations on trees

Trees can be thought of as a list of branches. When using list operations on trees, each branch is treated as a separate list and the operation is applied to each branch independently. It is tricky to predict the resulting data structure and therefore it is always important to check your input and output structures before and after applying any operation.

To illustrate how list operations work in trees, we will use a simple tree, a grid of points, and apply different list operations on it. We will then examine the output and its data structure.

Operations	Common list operation and how they apply to trees
List Item Select items at specific index in each branch	
List Item Select multiple indices to isolate part of the tree and perform one operation on such as ***Mass Addition***	
Split List Split the elements of branches into 2 trees at the specified index	
Shift List Shifts the elements of each branch	

Cull Pattern Culls each branch	

3_5_3: Grafting from lists to a trees

In some cases you need to turn a list into a tree where each element is placed in its own branch. Grafting can handle complex trees with branches of variable depths.

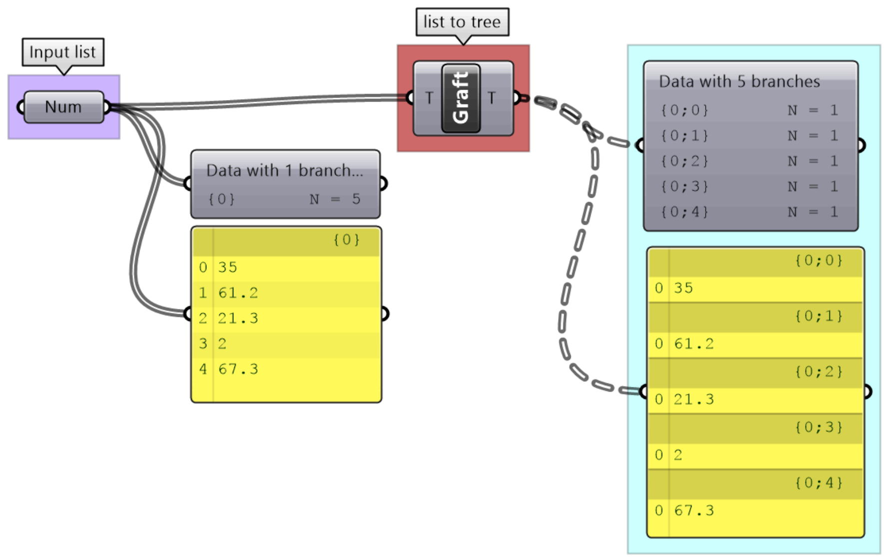


Figure (67): Grafting a tree creates a new branch for each element

It might feel unintuitive to complicate the data structure (from a simple list to a tree), but grafting is very useful when trying to achieve certain matching. For example if you need to add each element of one list with all the elements in the second list, then you will need to graft the first list before inputting to the addition process.

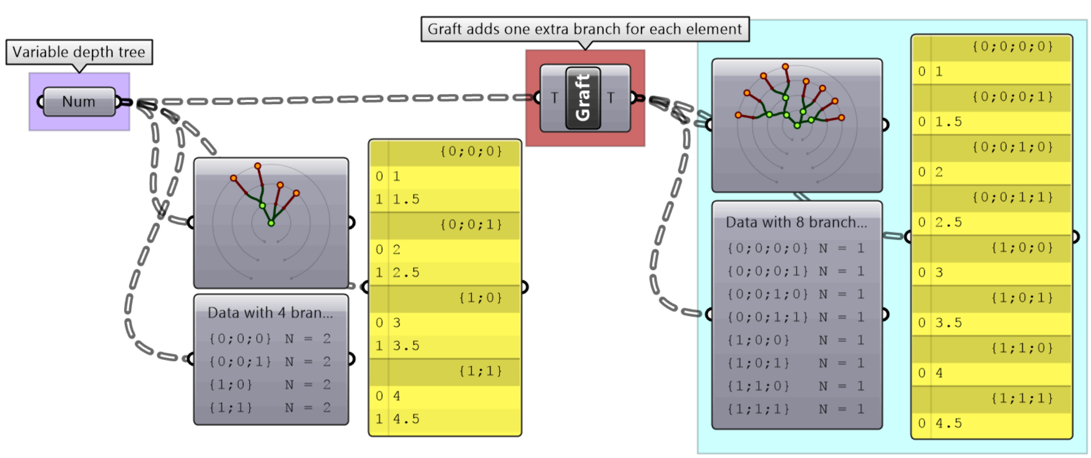


Figure (68): Grafting complex trees

3_5_4: Flattening from trees to lists

Other times you might need to turn your tree structure into a simple list. This is achieved with the flattening process. Data from each branch is extracted and sequentially attached to one list.

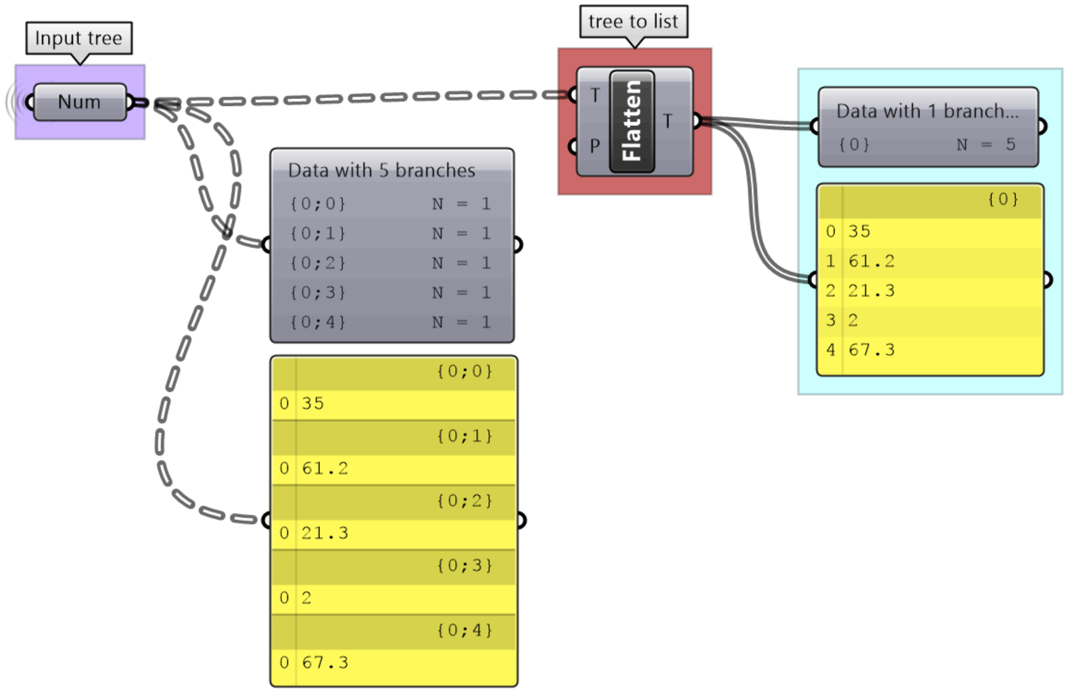


Figure (69): Flattening place all tree elements in one list

Flatten also can handle any complex tree. It takes the branches in order starting with the lowest index trunk and put all elements in one list.

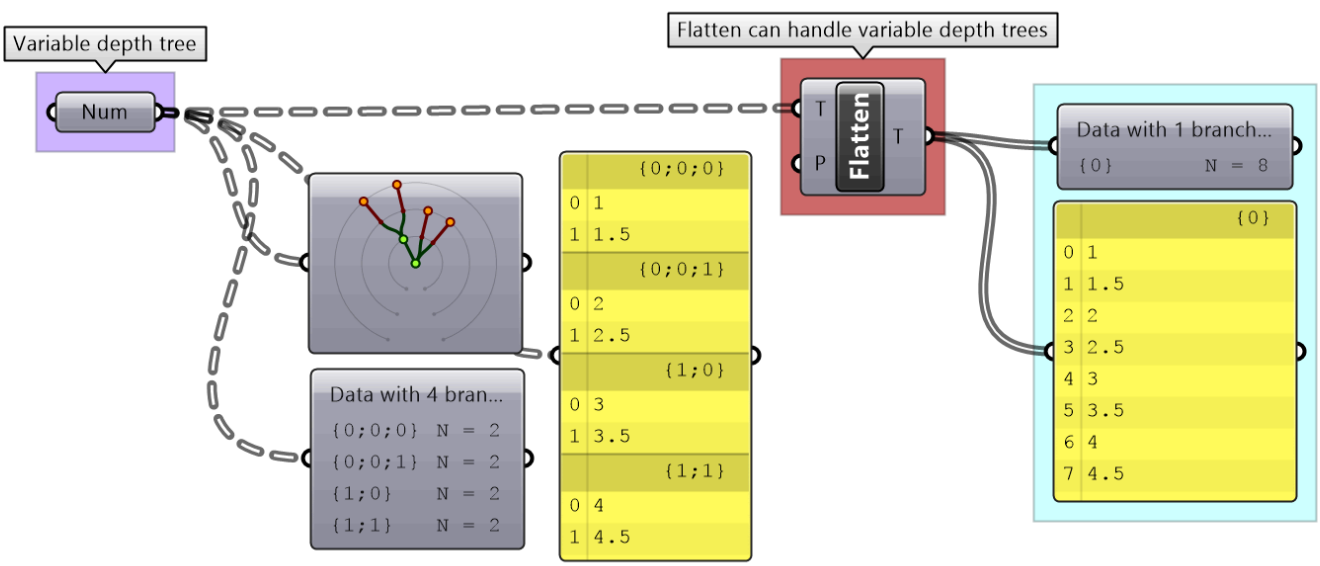


Figure (70): Flattening complex trees

3_5_5: Combining data streams

It is possible to compose a number of lists into a tree where each list becomes a branch in a new tree. It is different from the merging of lists where simply one bigger list is created.

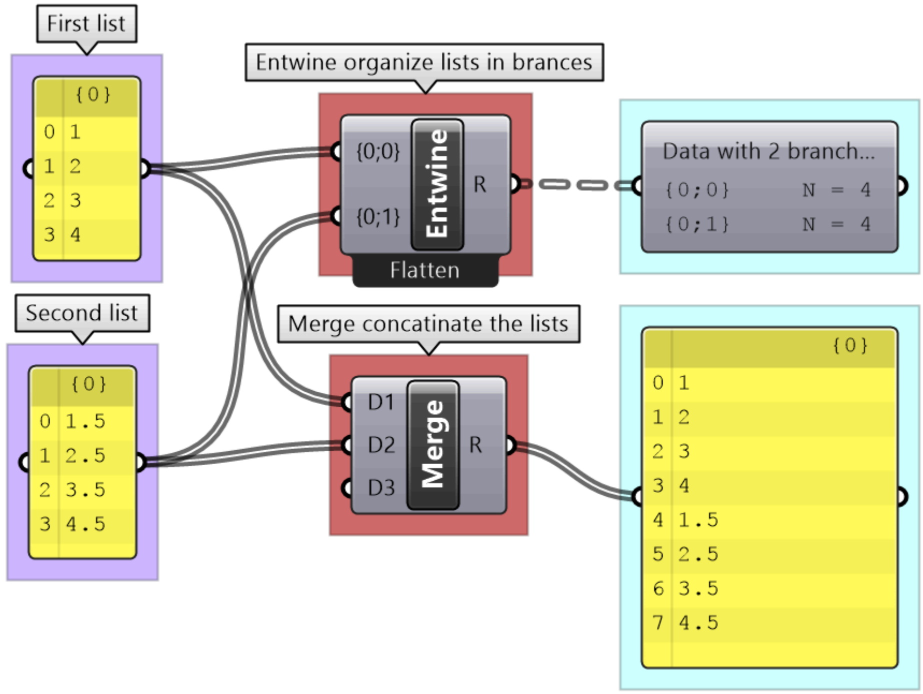


Figure (71): ***Entwine*** and ***Merge*** components combine lists into trees or bigger lists

3_5_6: Flipping the data structure

It is logical in some cases to flip the tree to change the direction of branches.This is specially useful in grids when points are organized in rows and columns (similar to a 2 dimensional array structure). Flipping causes corresponding elements across branches (have the same index in their branch) to be grouped in one branch. For example, a data tree that has 2 branches and 4 items in each branch, can be flipped into a tree with 4 branches and 2 elements in each branch.

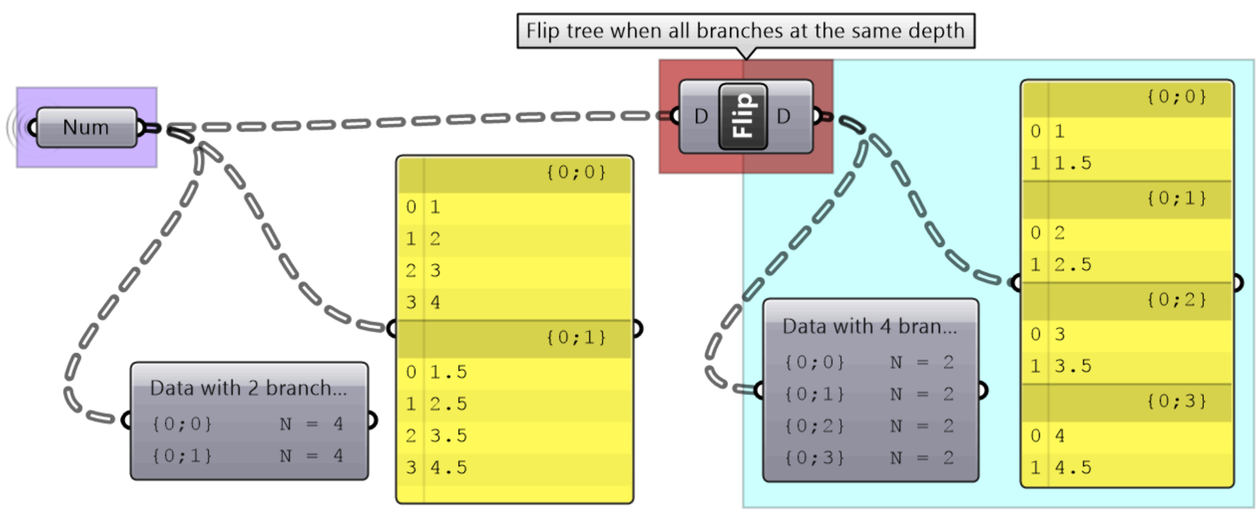


Figure (72): ***Flip*** helps reorganize data in a trees

If the number of elements in the branches are variable in length, some of the branches in the flipped tree will have “null” values.

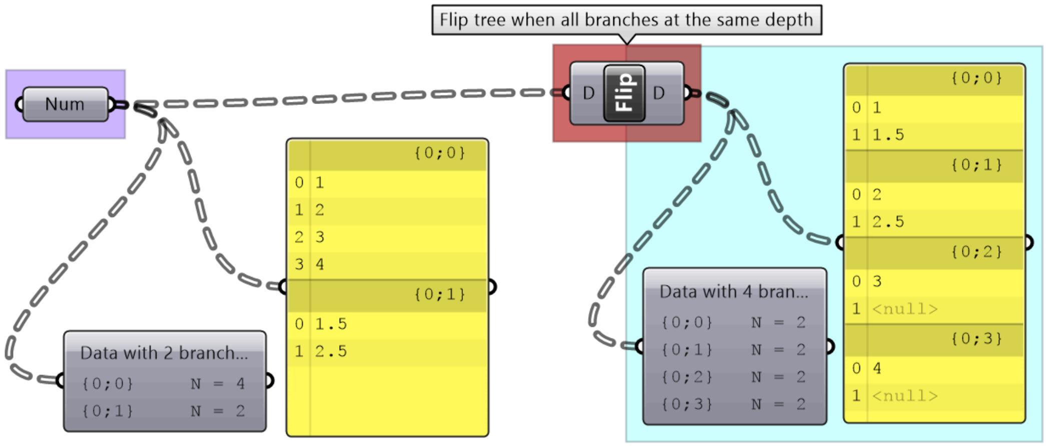


Figure (73): Add “null” when flipping trees with variable length branches

Flipping is one of the operations that cannot handle variable depth branches, simply because there is no logical solution to flip.

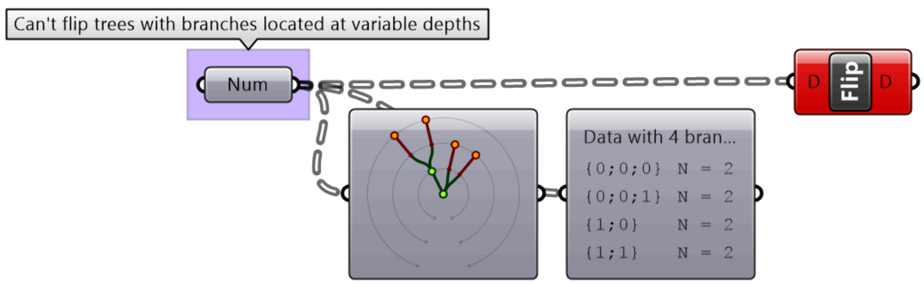


Figure (74): ***Flip*** fails when the input tree has variable depth branches

3_5_7: Simplifying the data structure

Processing data through multiple components can add unnecessary complexity to the data structure. The most common form is adding leading or trailing zeros to the paths addresses. Complex data structures are hard to match. ***Simplify Tree*** process helps remove empty branches. There are other operations such as ***Clean Tree*** and ***Trim Tree*** to help remove null elements, empty branches and reduce complexity. It is also possible to extract all branches as separate lists using the ***Explode Tree*** operation.

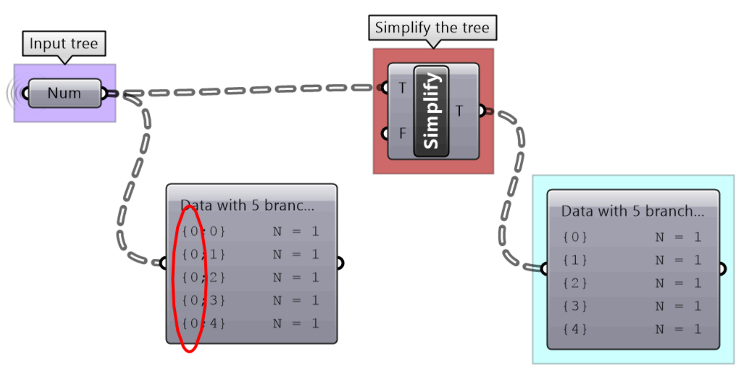
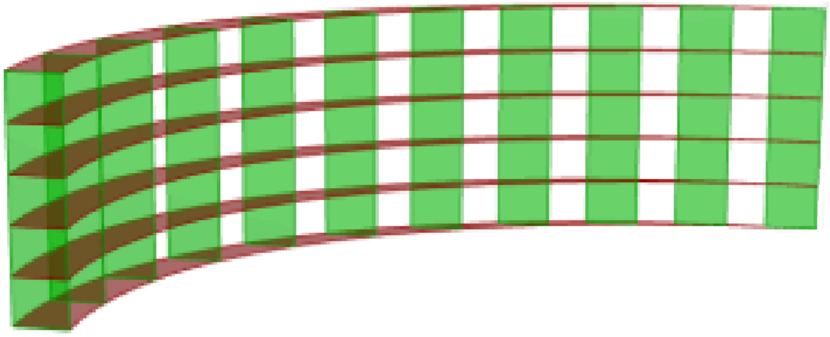
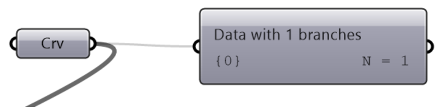
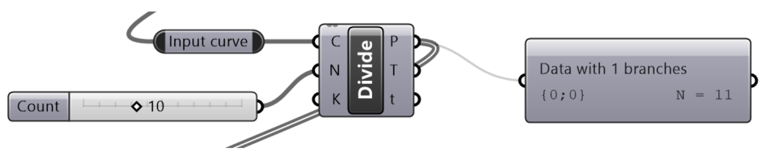
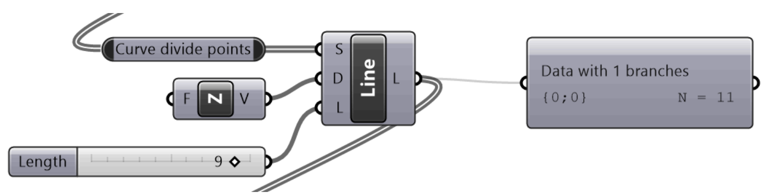
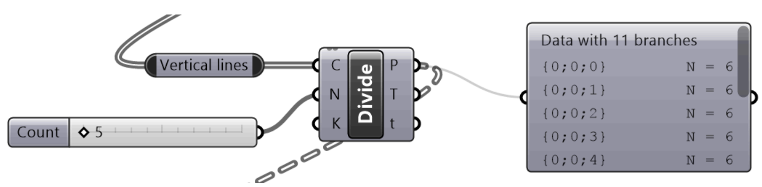
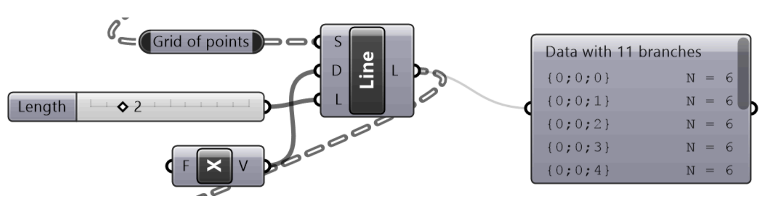
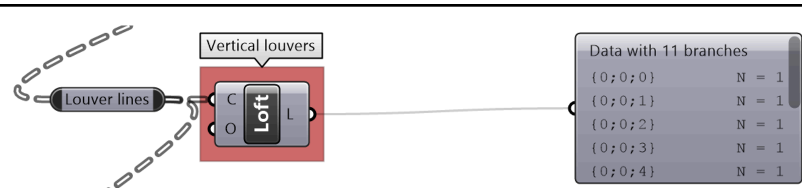


Figure (75): Paths can increase in complexity as more operations are applied to the data. ***Simplify*** helps remove empty branches

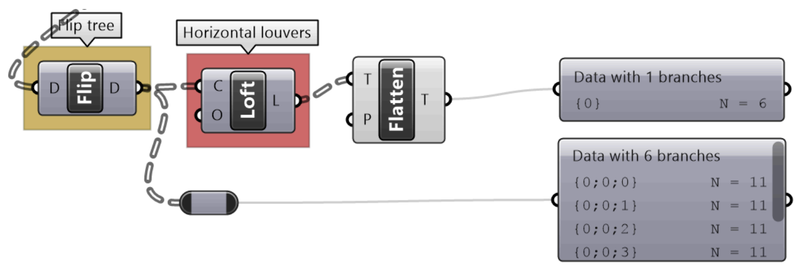
3_5_A Louvers tutorial

Given one curve on XY-Plane, create horizontal and vertical louvers as in the image



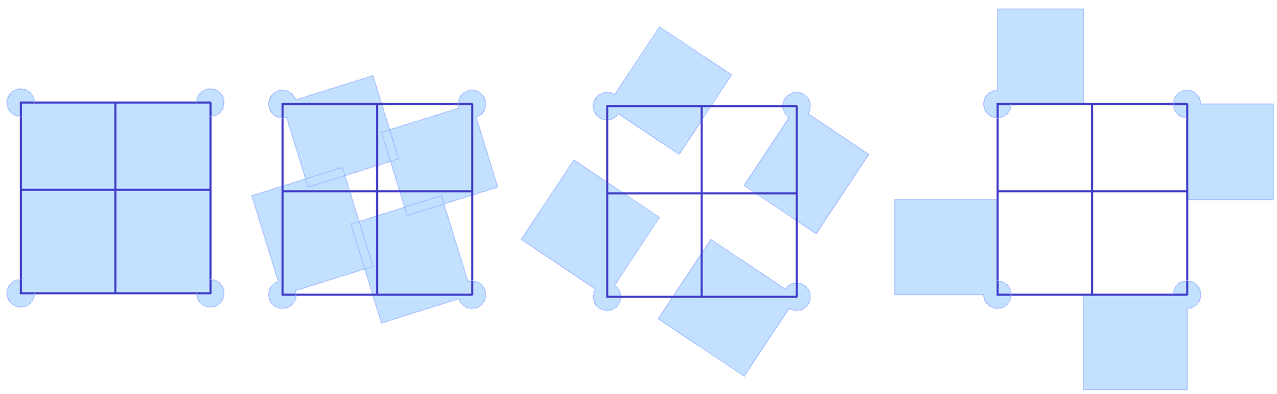
Solution	
Examine the **data structure** of output from each step before feeding it into the next process. input curve <u>data structure</u>: Single item (one branch and one item in the branch)	
Divide input curve to extract **points**. <u>Data structure</u>: list (one branch with 11 items). Note that the path has added leading “0”. This indicates the next layer of calculation.	
Create vertical **lines** at each point. <u>Data structure</u>: list (one branch with 11 items). Note that the path did not increase in complexity.	
Divide vertical lines to create a **grid of points**. <u>Data structure</u>: Tree (11 branches with 6 items). Note that the path has added leading “0”.	
Create horizontal **lines** at each point. <u>Data structure</u>:Tree (11 branches with 6 items). Note that the path did not increase in complexity.	
Create lofted **surfaces** through branches of lines. <u>Data structure</u>:Tree (11 branches with 1 item each). Note that the path did not increase in complexity.	

<table>
<tr>
<td>Flip the tree matrix and then create lofted surfaces through branches of lines.
<u>Data structure</u>:Tree (11 branches with 1 item each). Note that the path did not increase in complexity.

You can flatten the tree to create one list of horizontal louvers.</td>
<td>
</td>
</tr>
</table>

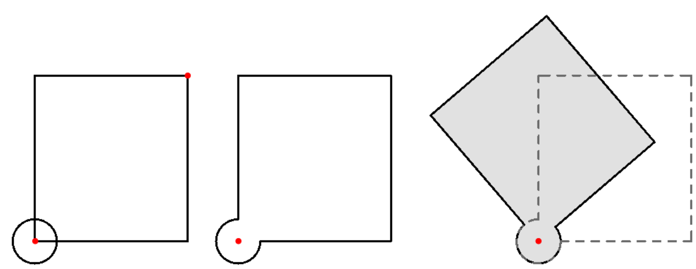
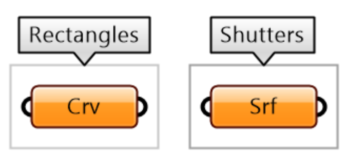
3_5_B Shutters

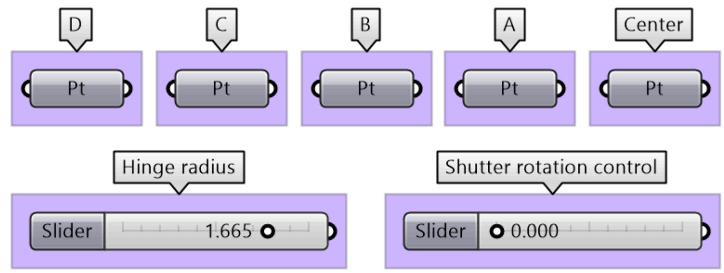
Given four corner points on a plane and a radius for the hinge, create a shutter that can open and shut as in the image using a rotation parameter.



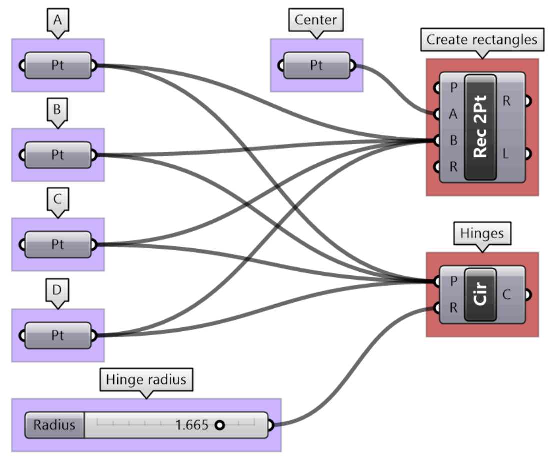
<table>
<tr>
<th colspan="2">Algorithm analysis</th>
</tr>
<tr>
<td>For each shutter there are two parts: the rectangle and the hinge.

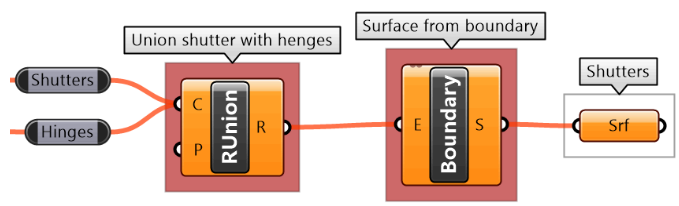
Union the rectangle and hinge, then allow rotating around the hinge.

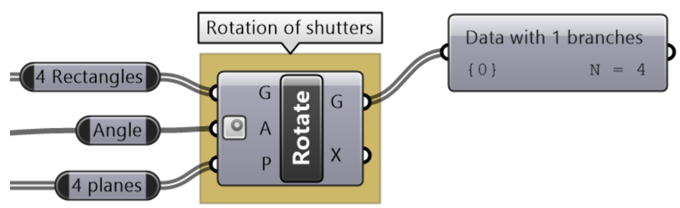
There is one rotation control to move all shutters together</td>
<td></td>
</tr>
<tr>
<th colspan="2">Solution steps</th>
</tr>
<tr>
<td>Output
Surface of the shutters
Curves for the frame</td>
<td>
</td>
</tr>
</table>

<table>
<tr>
<td>Input
The window four corner points (and center)
Hinge radius
Rotation angle parameter</td>
<td>
</td>
</tr>
<tr>
<td>Key processes

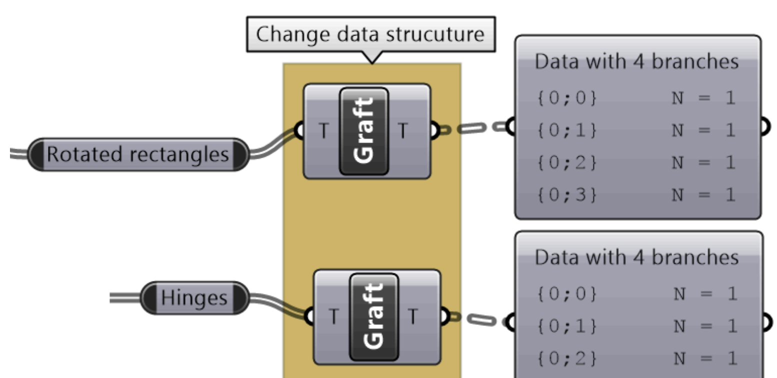
Create rectangle and hinges. Use the Rectangle component

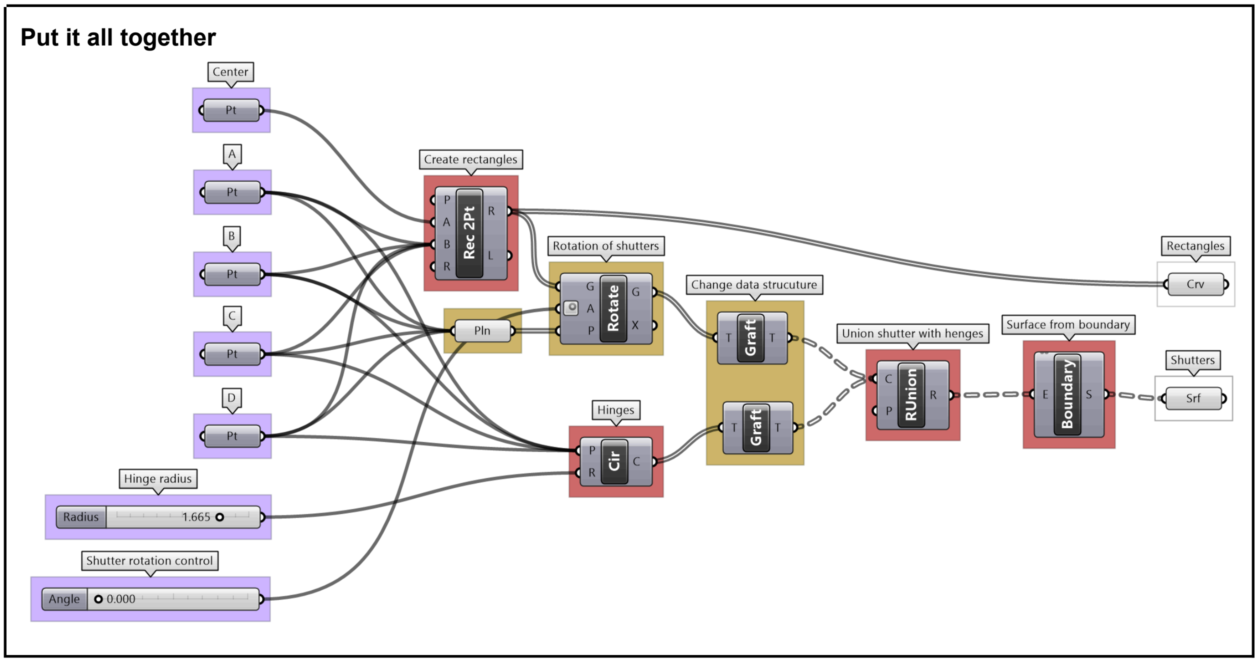
Union the curves. Use RUnion
Create a surface from the boundary. Use Boundary component</td>
<td>


</td>
</tr>
<tr>
<td>Intermediate process #1

Rotate the rectangles using the angle. Use Rotate component.</td>
<td>
</td>
</tr>
<tr>
<td>Intermediate process #2

Properly match the data structures of the rectangles and hinges before the region union.

Use Graft so that rectangles and hinges pair correctly.</td>
<td>
</td>
</tr>
</table>



3_6: Advanced tree operations

As your solutions increase in complexity, so will your data structures. We will discuss three advanced tree operations that are necessary to solve specific problems, or are used to simplify your solution by tabbing directly into the power of the data tree structure.

3_6_1: Relative items

The first operation has to do with solving the general problem of connectivity between elements in one tree or across multiple trees. Suppose you have a grid of points and you need to connect the points diagonally. For each point, you connect to another in the +1 branch and +1 index. For example a point in branch {0}, index [0], connects to the point in branch {1}, index [1].

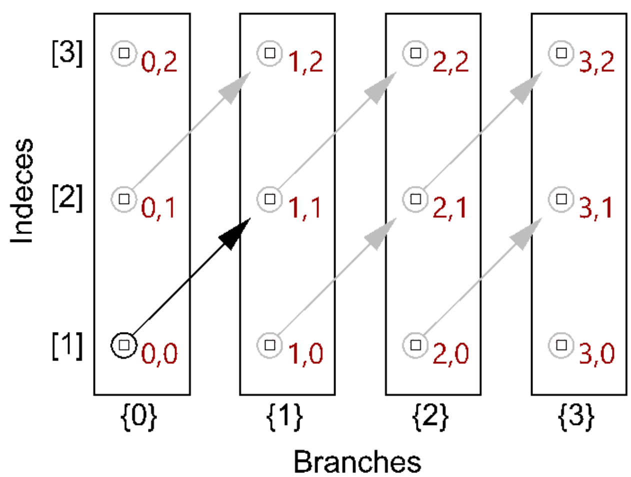


Figure (76): Relative Item mask {+1}[+1] create positive diagonal connectivity

In Grasshopper, the way you communicate the offset is expressed with an offset string in the format "{branch offset}[index offset]". In our example, the string to connect points diagonally is "{+1}[+1]". Here is an example that uses relative tree component in Grasshopper. Notice that the relative item component creates two new trees that correlate in the manner specified in the offset string.

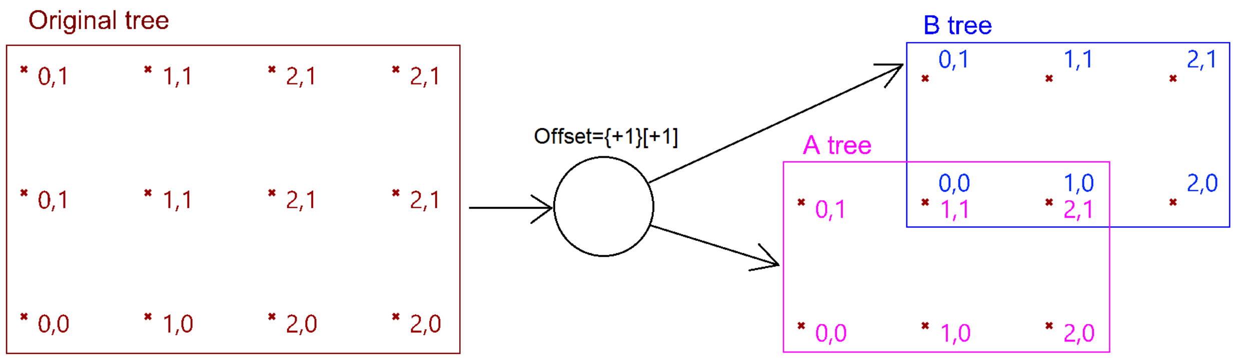


Figure (77): Relative Item mask {+1}[+1] breaks the original tree into 2 new trees with diagonal connectivity

Here is an example implementation in Grasshopper where we define relative items in one tree, then connect the two resulting trees with lines using the ***Relative Item*** component.

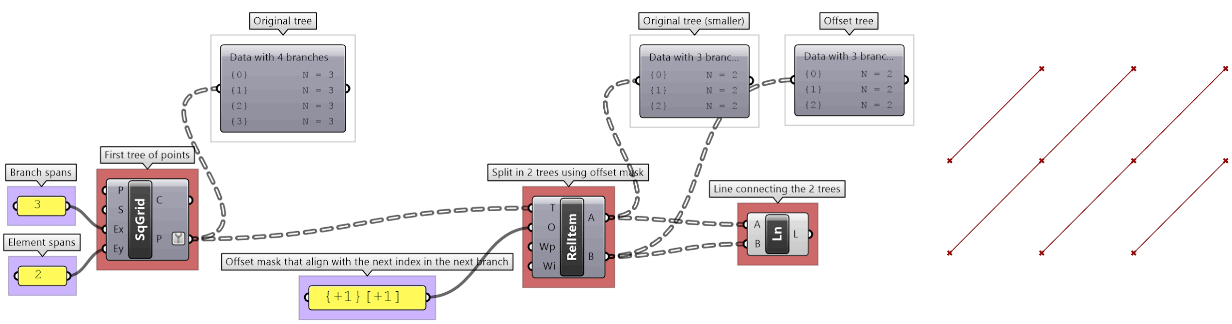
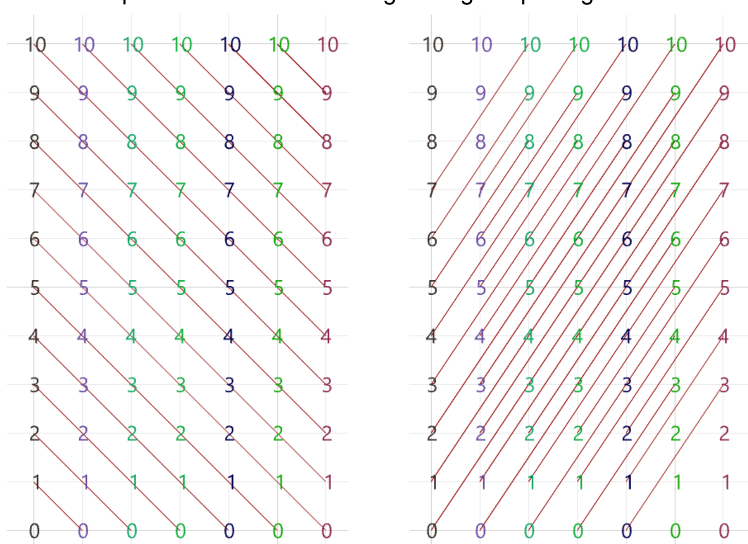
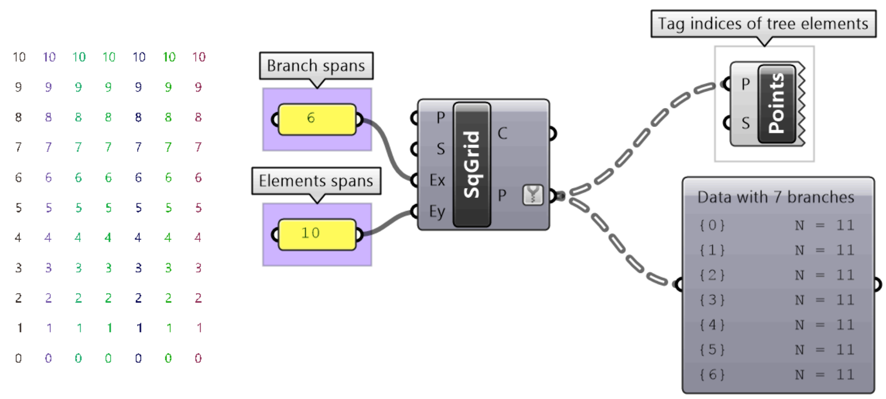


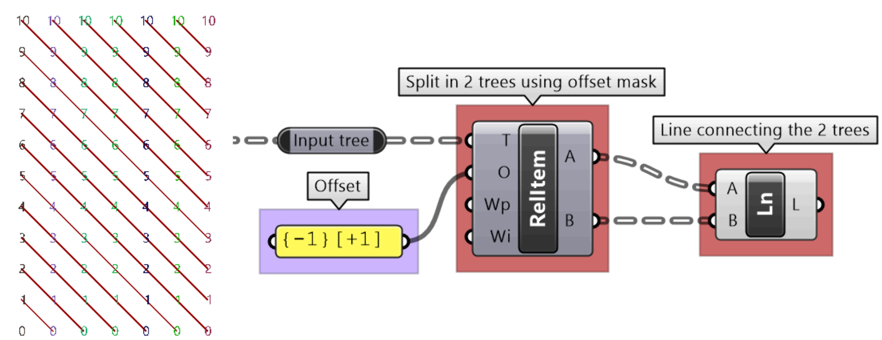
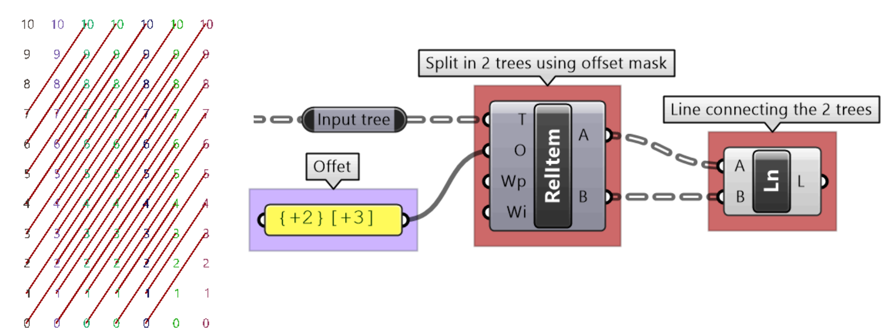
Figure (78): ***Relative Item*** with mask {+1}[+1] in Grasshopper

3_6_1_A Relative item pattern tutorial #1

Create the pattern shown in the image using a square grid of 7 branches where each branch has11 elements.



<table>
<tr><th colspan="2">Solution</th></tr>
<tr><td colspan="2">Define the {branch_offset} [index_offset]</td></tr>
<tr><td>Create the grid</td><td>
</td></tr>
<tr><td>Create relative trees that connect each element with -1 branch and +1 index: {-1}[+1]

Create lines to connect the 2 relative trees.</td><td>
</td></tr>
<tr><td>Change the offset to {+2}[+3] to create the second connections</td><td>
</td></tr>
</table>

We showed how to define relative items in one tree, but you can also specify relative items between 2 trees. You'll need to pay attention to the data structure of the two input trees and make sure they are compatible. For example, if you connect each point from the first tree with another point from a different tree with the same index, but +1 branch, then you can set the offset string to be {+1}[0].

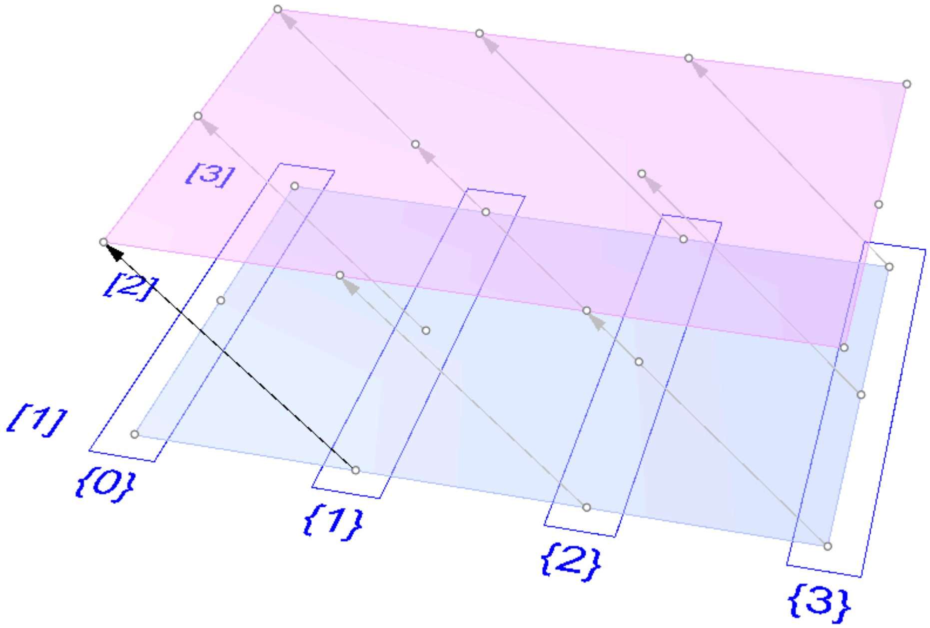


Figure (79): ***Relative Items*** create connections across multiple trees

The input to the ***Relative Items*** component is two trees and the output is two trees with corresponding items according to the offset string.

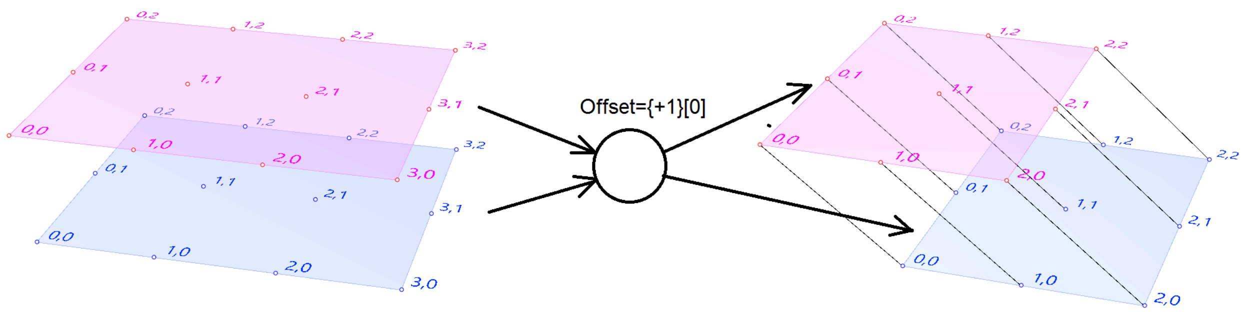


Figure (80): The offset mask of the ***Relative Items*** generates new trees with the desired connections

The following GH definition achieves the above:

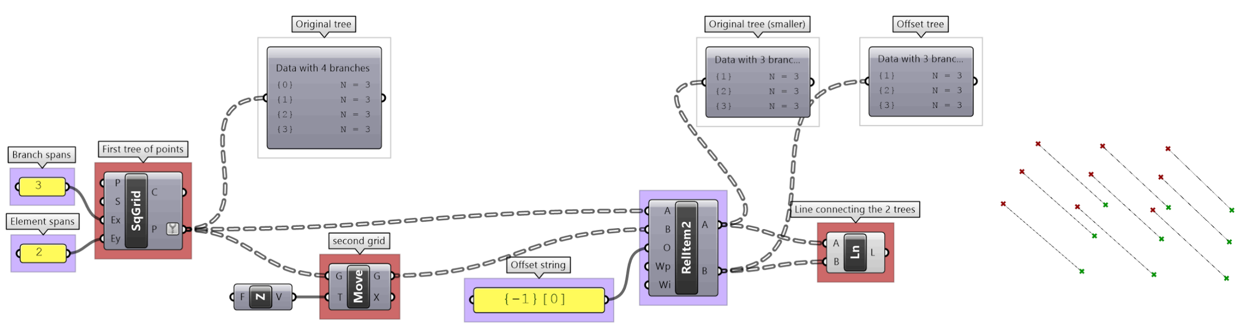
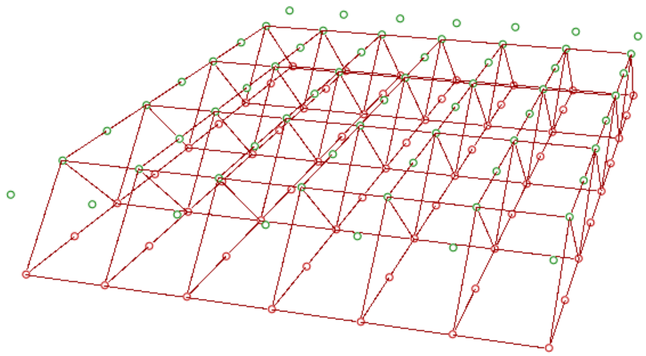


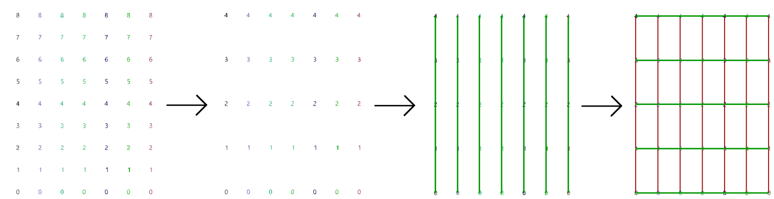
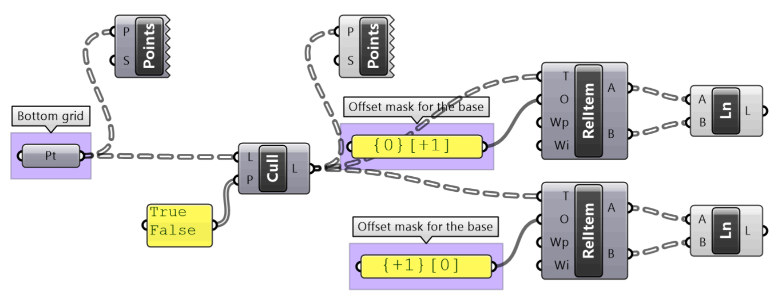
Figure (81): ***Relative Items*** implementation in Grasshopper

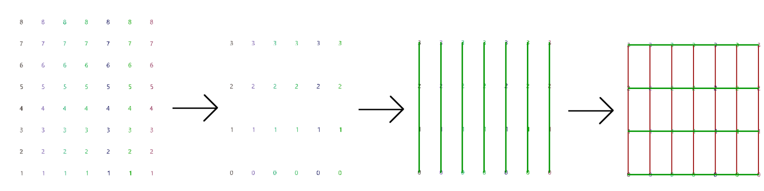
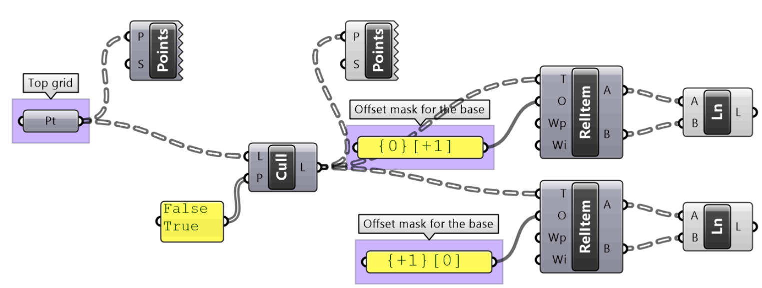
3_6_1_B Relative item truss tutorial #2

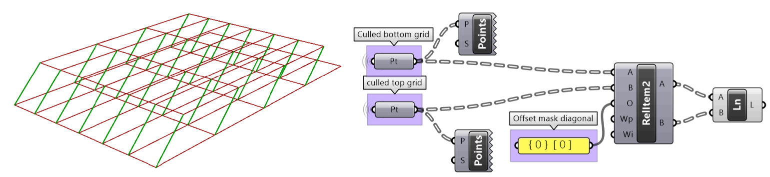
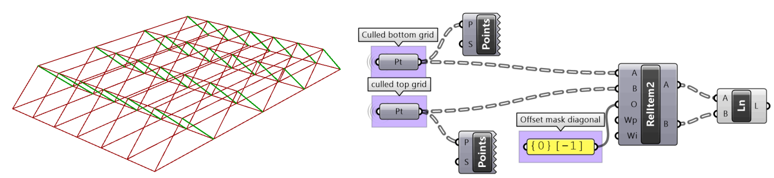
Use relative items between 2 bounding grids to generate the structure shown in the image.



<table>
<tr><th colspan="2">Solution</th></tr>
<tr><td colspan="2">Create the connections for the bottom tree</td></tr>
<tr><td>Cull every other index and keep the same number of branches (cull indices 1, 3,...)

Define the offset strings for RelativeItem components to create the vertical and horizontal connections</td><td></td></tr>
<tr><td>Grasshopper definition</td><td>
</td></tr>
<tr><td colspan="2">Create the connections for the top tree</td></tr>
<tr><td>Cull every other index and keep the same number of branches. (cull indices 0, 2,...)

Define the offset strings for RelativeItem components to create the vertical and horizontal connections</td><td></td></tr>
<tr><td>Grasshopper definition</td><td>
</td></tr>
<tr><td colspan="2">Connections between the bottom and top trees</td></tr>
</table>

Use culled grids, then define first offset string for *RelativeItems* component to create the first set of cross lines: {0}[0]	
Define second offset string for *RelativeItems* component to define the second set of cross lines: {0}[-1]	

3_6_2: Split trees

The ability to select a portion of a tree, or split into two parts is a very powerful tree operation in Grasshopper. You can split the tree using a string mask using specific syntax (see examples below). The mask filters, or helps select, the positive part of your tree. The portion of the tree left, is also given as an output and is called the negative part of the tree. Since all trees are made out of branches and indices, the split mask should include information about which branches and indices within these branches to split along. Here are the rules of the split mask:

Split tree mask: syntax and general rules	
{ ; ; }	Use curly brackets to enclose the mask for the tree branches.
[ ]	Use square brackets to enclose the mask for the elements (leaves). Can be omitted if select all items or use [*]
( )	Round brackets are used for organizing and grouping
*****	Any number of integers in a path. The asterisk also allows you to include all branches, no matter what their paths look like
?	Any single integer
6	Any specific integer
!6	Anything <u>except</u> a specific integer
(2,6,7)	Any one of the specific integers in this group.
!(2,6,7)	Anything <u>except</u> one of the integers in this group.
(2 to 20)	Any integer in this range (including both 2 and 20).
!(2 to 20)	Any integer <u>outside of</u> this range.
(0,2,...)	Any integer part of this infinite sequence. Sequences have to be at least two integers long, and every subsequent integer has to be bigger than the previous one (sorry, that may be a temporary limitation, don't know yet).

(0,2,...,48)	Any integer part of this finite sequence. You can optionally provide a single sequence limit after the three dots.
!(3,5,...)	Any integer not part of this infinite sequence. The sequence doesn't extend to the left, only towards the right. So this rule would select the numbers 0, 1, 2, 4, 6, 8, 10, 12 and all remaining even numbers.
!(7,10,21,...,425)	Any integer not part of this finite sequence.
{ * }[(0 to 4) **or** (6,11,41) **]**	It is possible to combine two or more rules using the boolean and/or operators. The example selects the first five items in every list of a tree and also the items 7, 12 and 42.

Here are some examples of valid split masks.

Split by branches	
{ * }	Select all (the whole tree output as positive, and negative tree will be empty)
{ *; 2 **}**	Select the third branch
{ *; (0,1) **}**	Select the first two end branches
{ *; (0, 2, …) **}**	Select all even branches
Split by branches and leaves	
{ * }[(1,3,...)**]**	Select elements located at odd indices in all branches
{ *; 0 **}[**(1,3,...)**]**	Select elements located at odd indices in the first branch
{ *; (0, 2) **}[**(1,3,...)**]**	Select elements located at odd indices in the first and third branches
{*; (0,2,...) **} [** (1,3,...) **]**	Select elements located at odd indices in branches located at even indices
{*; (0,2,...) **} [**(0) **or** (1,3,...)**]**	Select elements located at odd indices, and index “0”, in branches located at even indices

One of the common applications that uses split tree functionality is when you have a grid of points that you like to transform a subset of. When splitting, the structure of the original tree is preserved, and the elements that are split out are replaced with null. Therefore, when applying transformation to the split tree, it is easy to recombine back.
Suppose you have a grid with 7 branches and 11 elements in each branch, and you’d like to shift elements between indices 1-3 and 7-9. You can use the split tree to help isolate the points you need to move using the mask: {*}[(1,2,3) or (7,8,9)], move the positive tree, then recombine back with the negative tree.

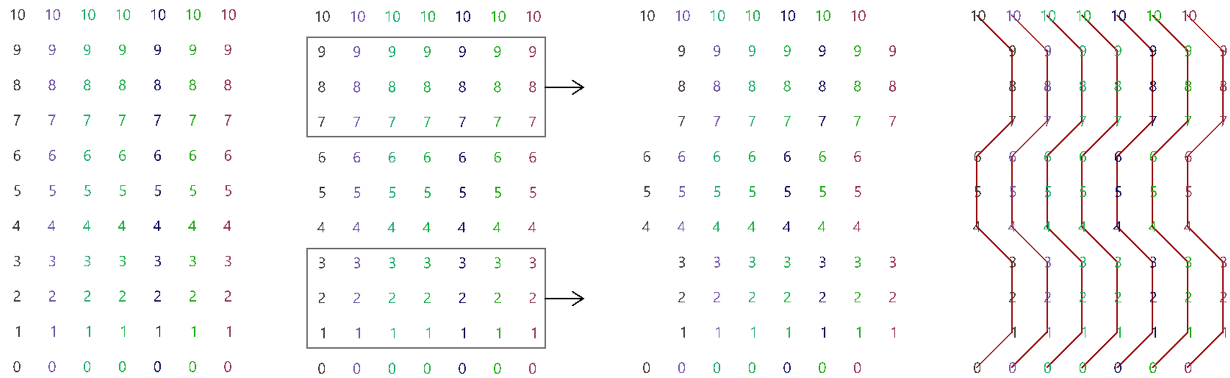


Figure (82): ***Split tree*** allows operating on a subset of the tree with the possibility to recombine back

This is the GH definition that does the above using the ***Split Tree*** component.

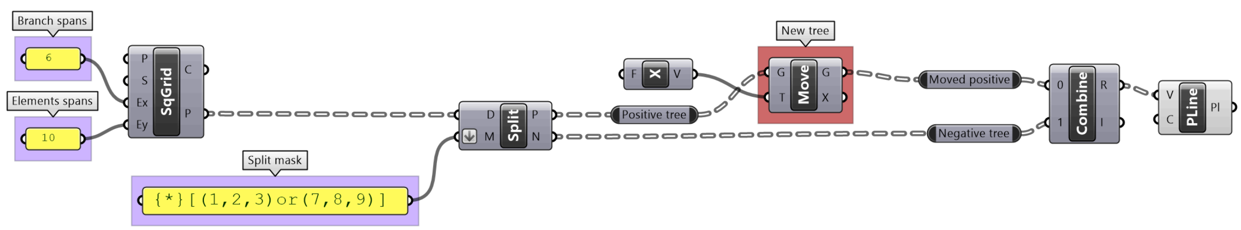
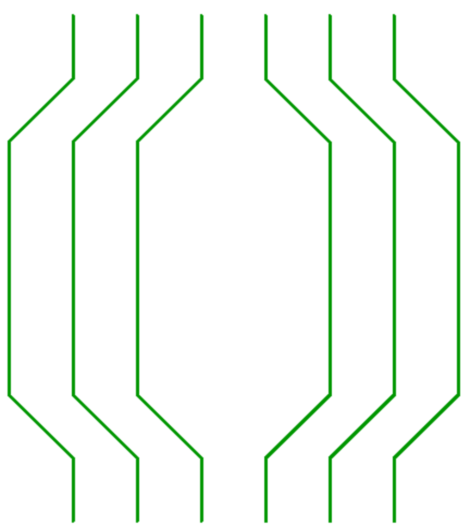


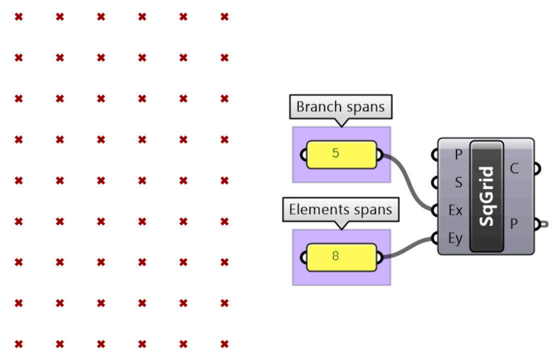
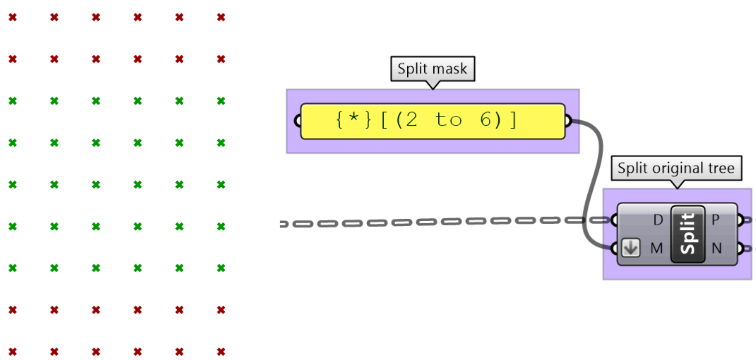
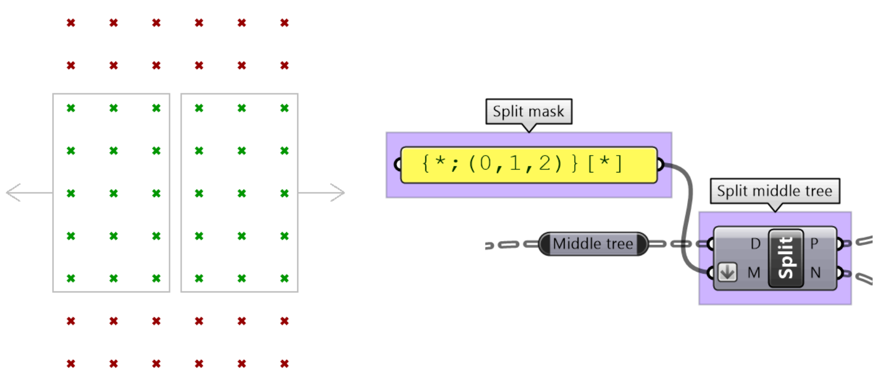
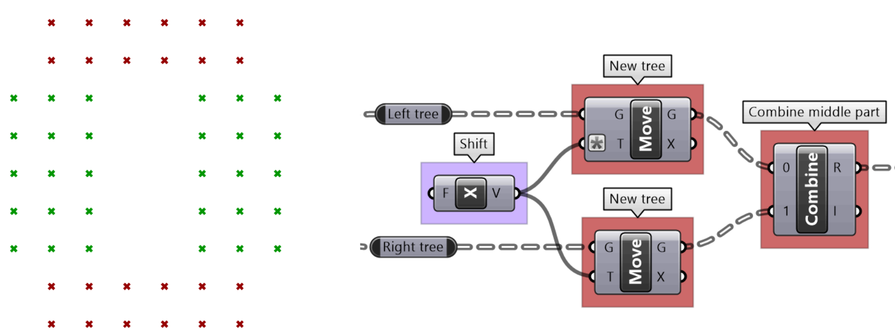
Figure (83): ***Split tree*** Grasshopper implementation of Figure (82)

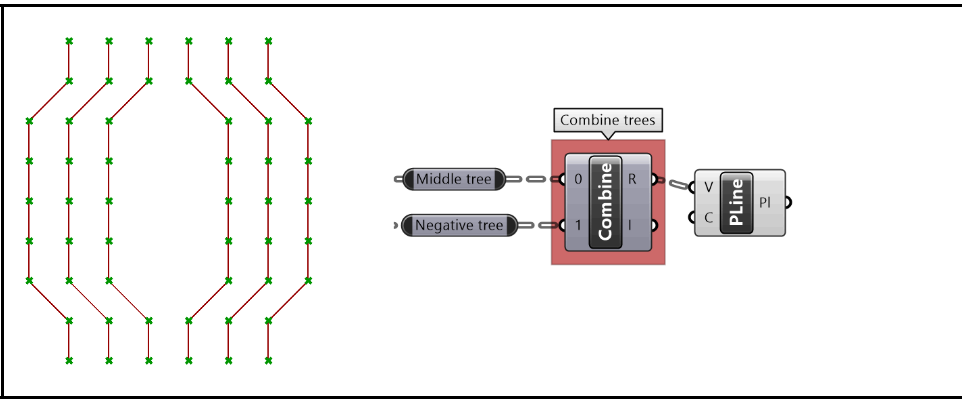
One of the advantages of using ***Split Tree*** over relative trees is that the split mask is very versatile and it is easier to isolate the desired portion of the tree. Also the data structure is preserved across the negative and positive trees which makes it easy to recombine the elements of the tree after processing the parts.

3_6_2_A Split tree pattern tutorial

Given a 6x9 grid, use the split tree to generate the following pattern.

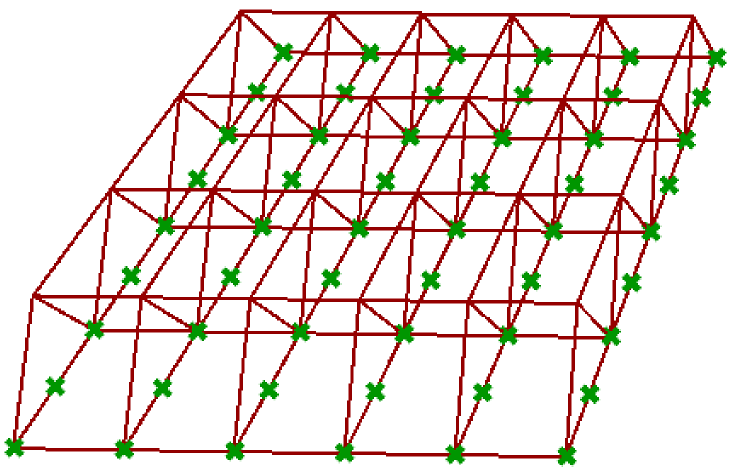


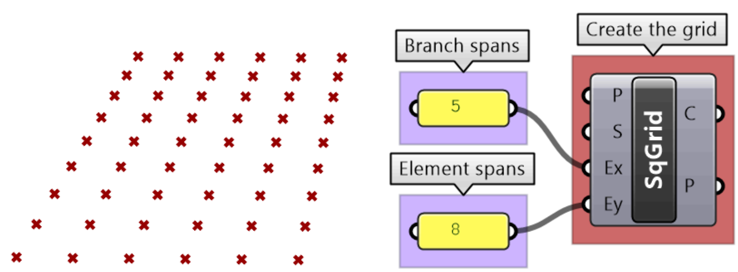
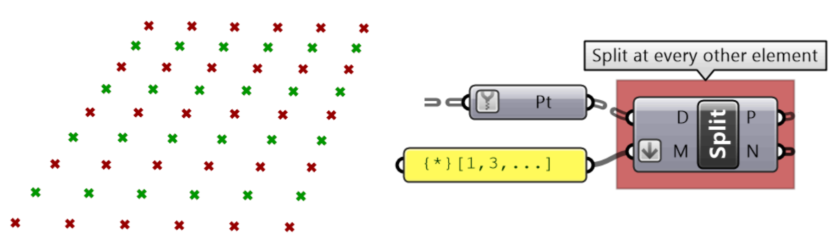
Solution steps	
Create the grid	
Split the tree to isolate the middle part	
Split the middle part into two new parts	
Move the two middle parts in opposite directions then recombine them	

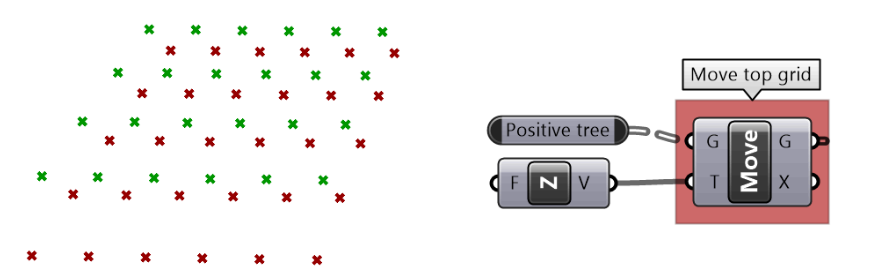
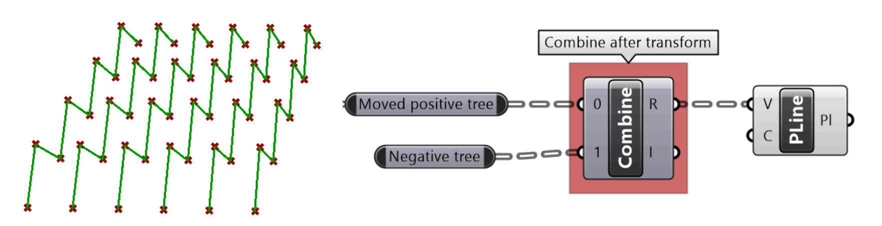
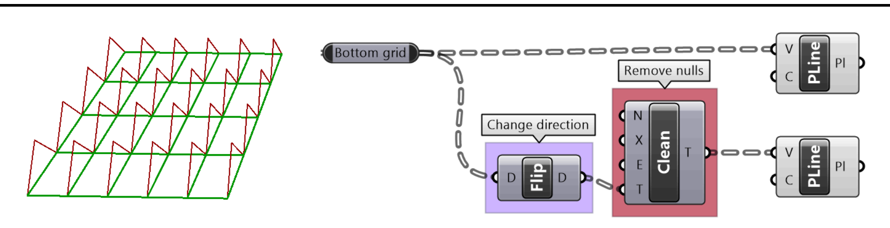
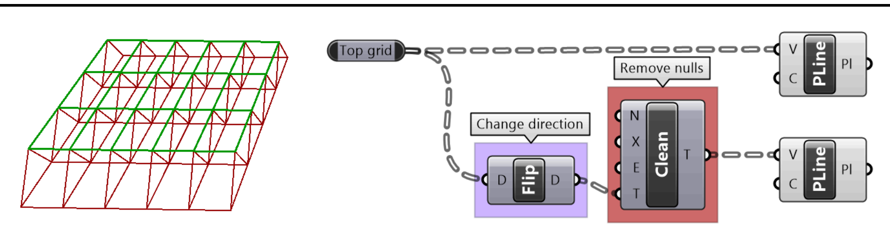
Recombine the middle part with the rest of the tree and create polylines through each branch elements	

3_6_2_B Split tree truss tutorial

Given a grid, create the following truss system using the split tree method.



Solution	
Create the 6x9 grid	
Split at every other element	

Move positive tree vertically	
Combine positive and negative trees And create a polyline through each branch	
Create bottom curves using negative tree	
Create top curves using positive tree	

3_6_3: Path mapper

When dealing with complex data structures such as the Grasshopper data trees, you'll find that you need to simplify or rearrange your elements within the tree. There are a few components offered in Grasshopper for that purpose such as ***Flatten***, ***Graft*** or ***Flip***. While very useful, these might not suffice when operating on multiple trees or needing custom rearrangement. There is one very powerful component in Grasshopper that helps with reorganizing elements in trees or changing the tree structure called the ***Path Mapper***. It is perhaps the least intuitive to use and can cause a loss of data, but it is also the only way to find a solution in some cases, and hence it pays to address here.
The ***Path Mapper*** maps data between source and target paths. The source path is fixed, and is given by the input tree. You can only set the target path. There is a set of constants that you can use to help construct the mapping. Those are listed in the table below.

item_count	Number of items in the current branch
path_count	Number of paths (branches) in the tree
path_index	Index of the current path

Let's start by familiarizing ourselves with the syntax using built-in mappings inside the ***Path Mappers***. If you right-mouse-click on the mapper components, you can open the editor, and also access a number of default mapping functions that are commonly used.

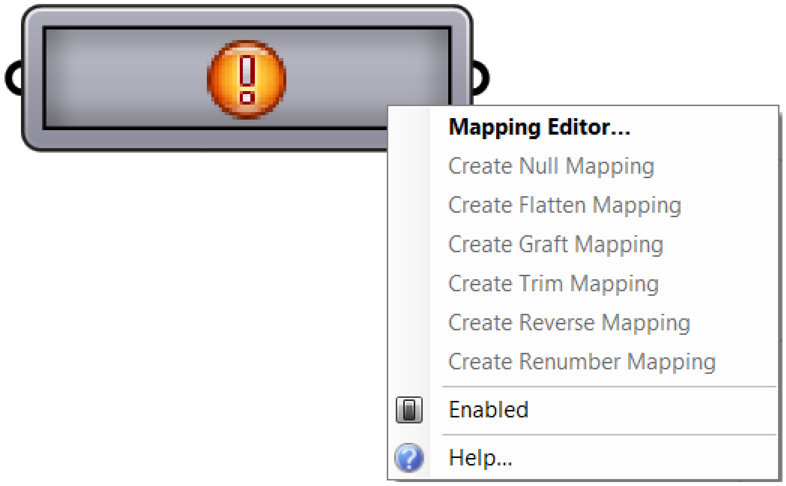
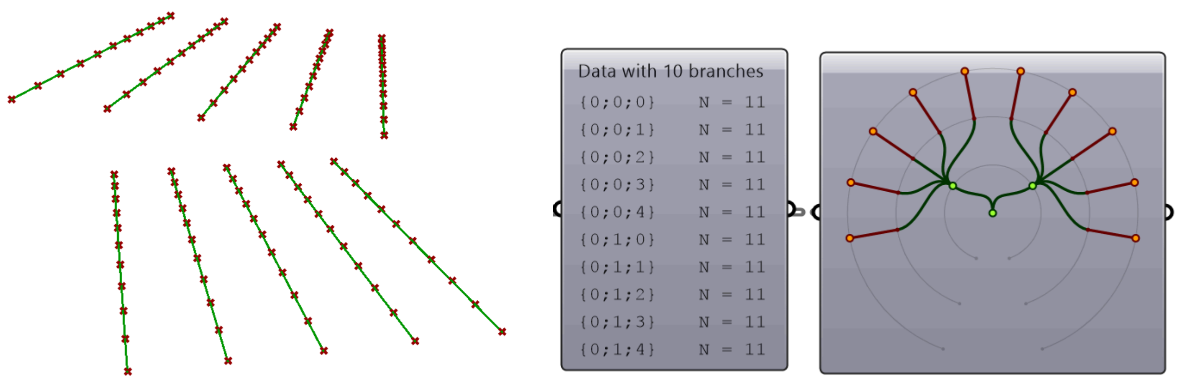
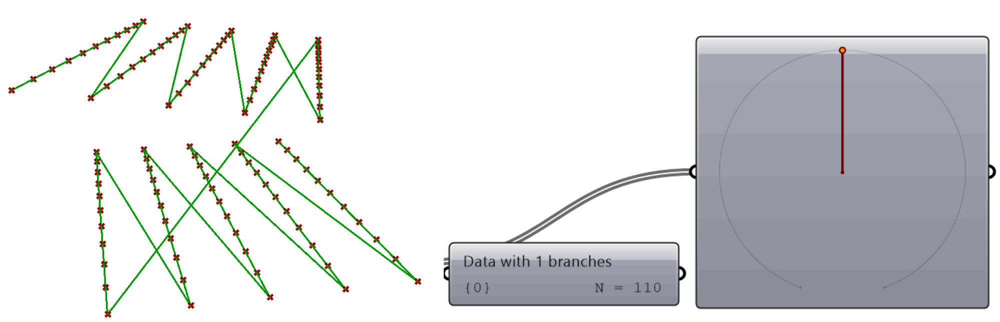
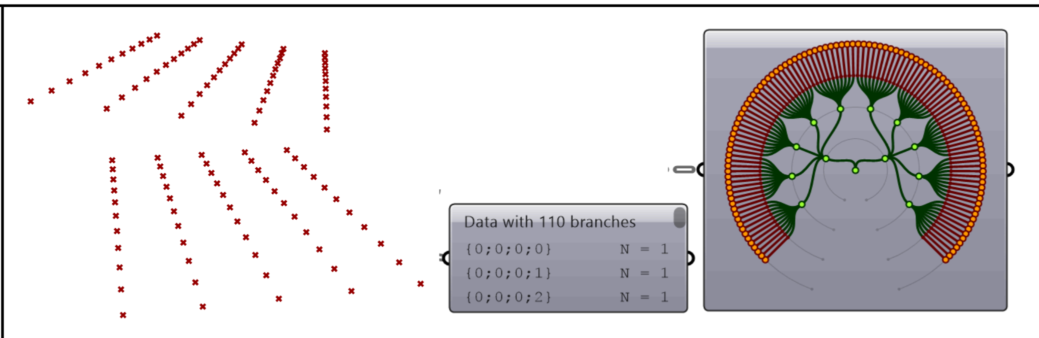
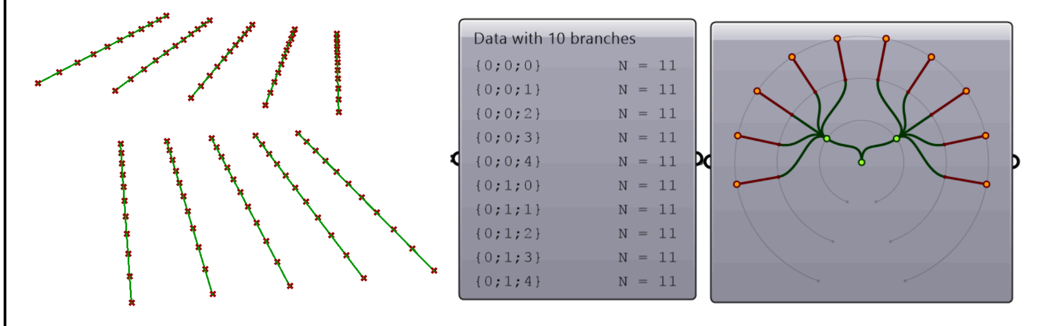
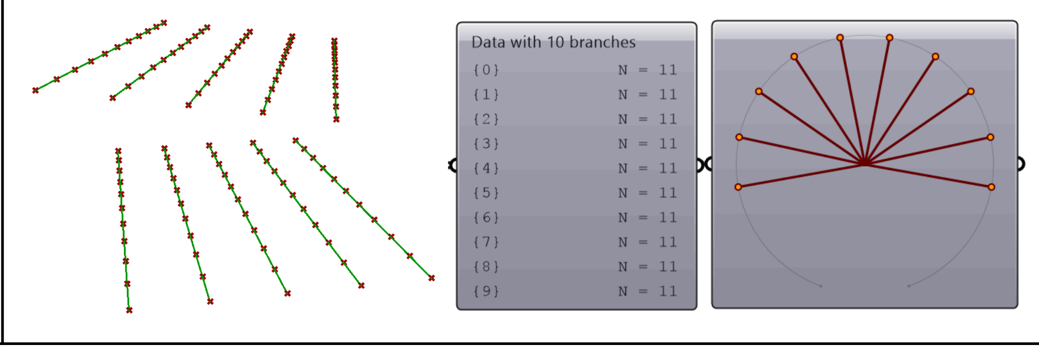


Figure (84): ***Path Mapper*** built-in mappings

The following example examines different built-in mapping in the ***Path Mapper*** and how it changes the data structure. The ***Polyline*** component creates one polyline through each branch of the tree. Notice how different mapping affects the result.



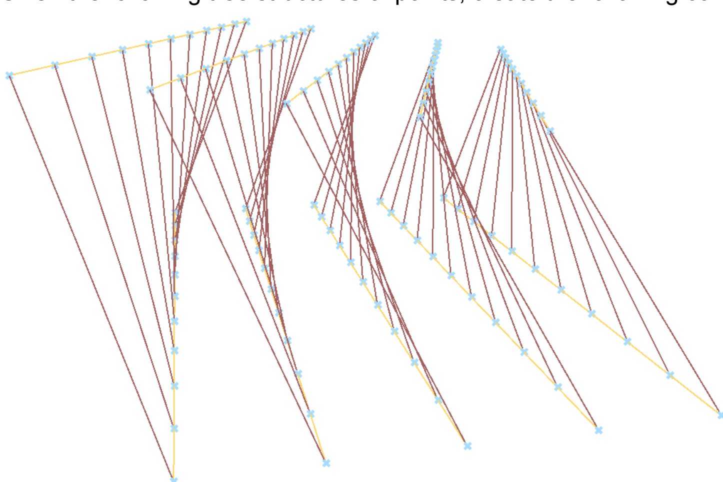
Built-in mappings inside the Path Mapper component	
Null Mapping	Does not change anything.
Flatten Mapping	

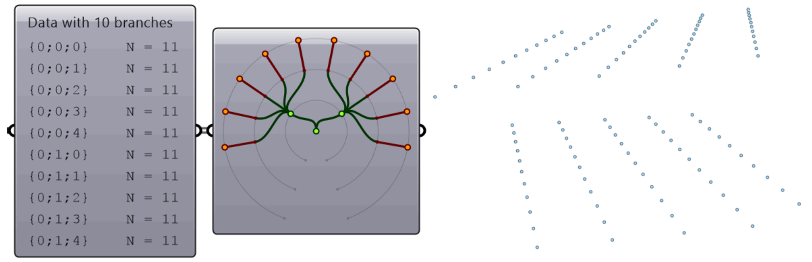
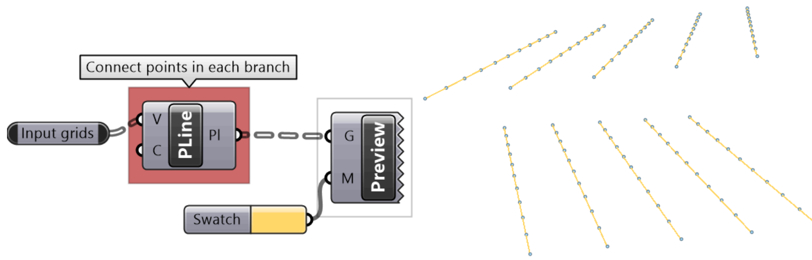
Graft Mapping	
Reverse Mapping	
Renumbering Mapping	

For more details about the Path Mapper, please refer to the help inside the component in Grasshopper.

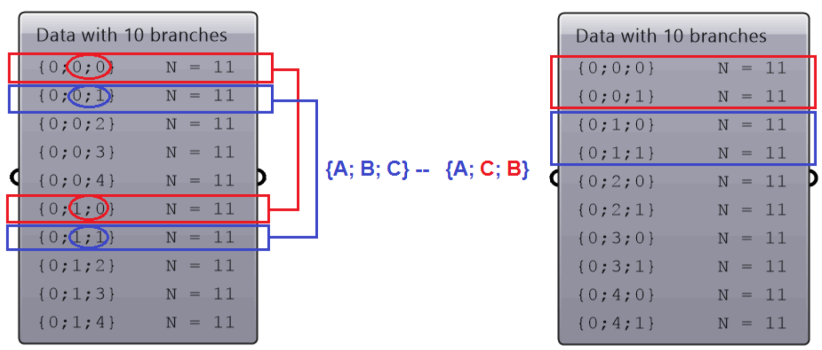
3_6_3_A Partitions tutorial

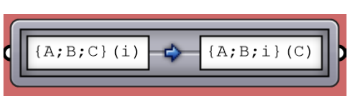
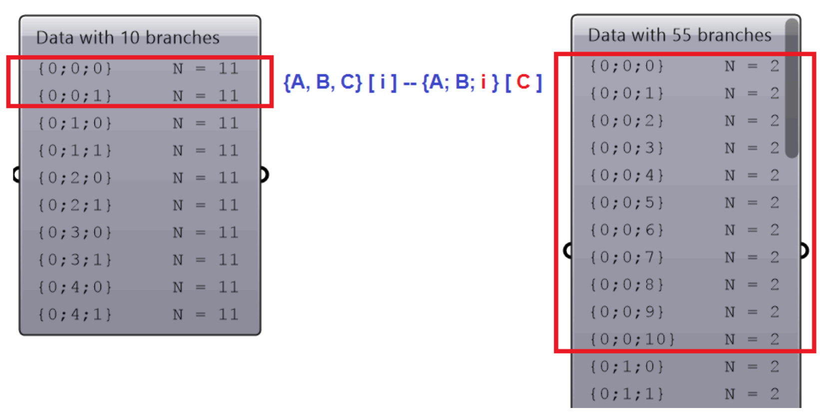
Given the following tree structures of points, create the following connections.



<table>
<tr><th colspan="2">Solution</th></tr>
<tr><td>The input has two trees, and each has 5 branches with 11 elements in each branch, a total of 10 branches.</td><td>
</td></tr>
<tr><td>A Polyline is used to connect the elements in each branch</td><td>
</td></tr>
<tr><td colspan="2">To create the vertical connections, you need to create a branch for each 2 corresponding elements across the 2 trees, then use Polyline to connect them
1- Analyze the paths of the trees
2- Come up with a mapping that generates the desired grouping</td></tr>
<tr><td>First, group corresponding branches across the 2 trees.

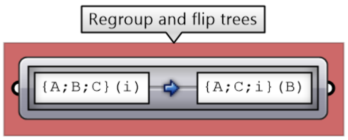
That can be achieved by switching the last two integers in the paths:

</td><td>
</td></tr>
<tr><td>Second, Flip each of the 5 trees. Since the branches have 11 elements each, flipping each tree will create 11 branches with 2 elements in each branch. Total of 55 branches.

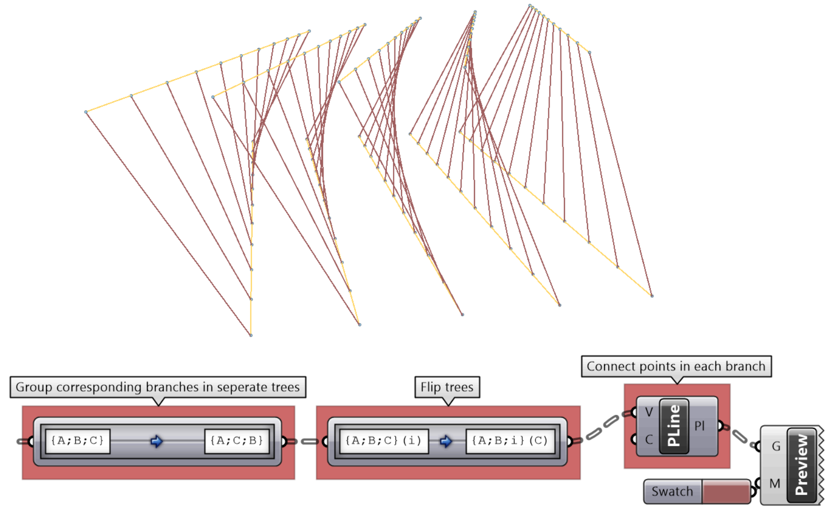
You flip by switching the last integer of the path with the element index:

</td><td>
</td></tr>
</table>

Finally, a *Polyline* makes the vertical connections.

Note: You can combine the 2 mappings in one step as in the following:

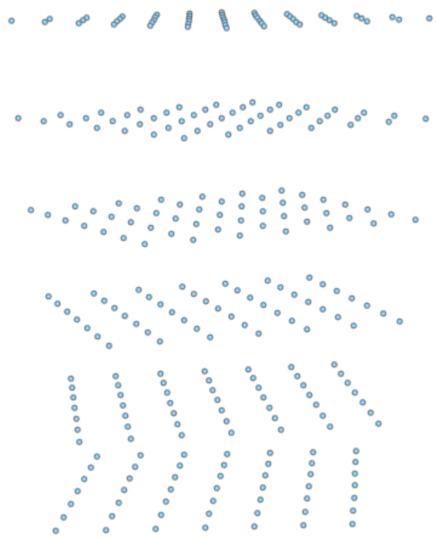


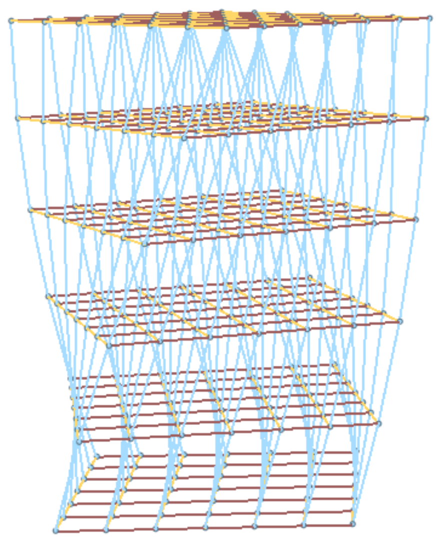
Combining is not always possible, but it can save processing time and size.

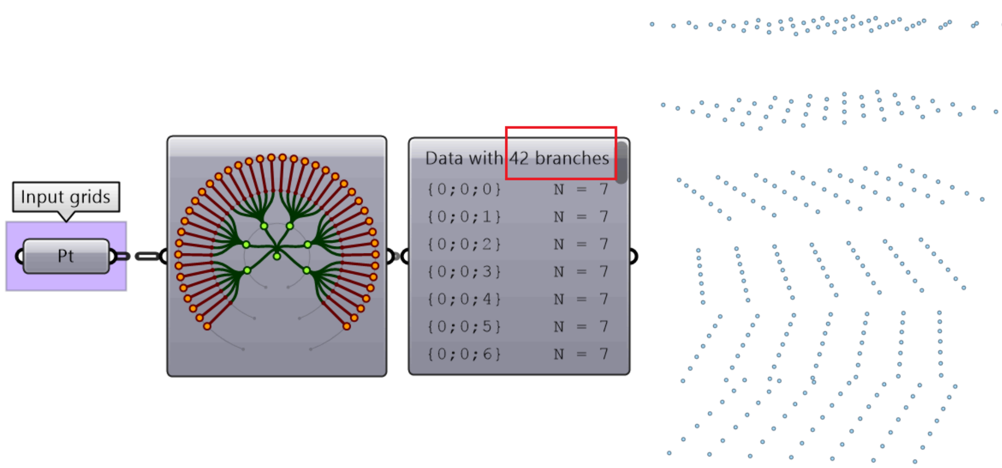


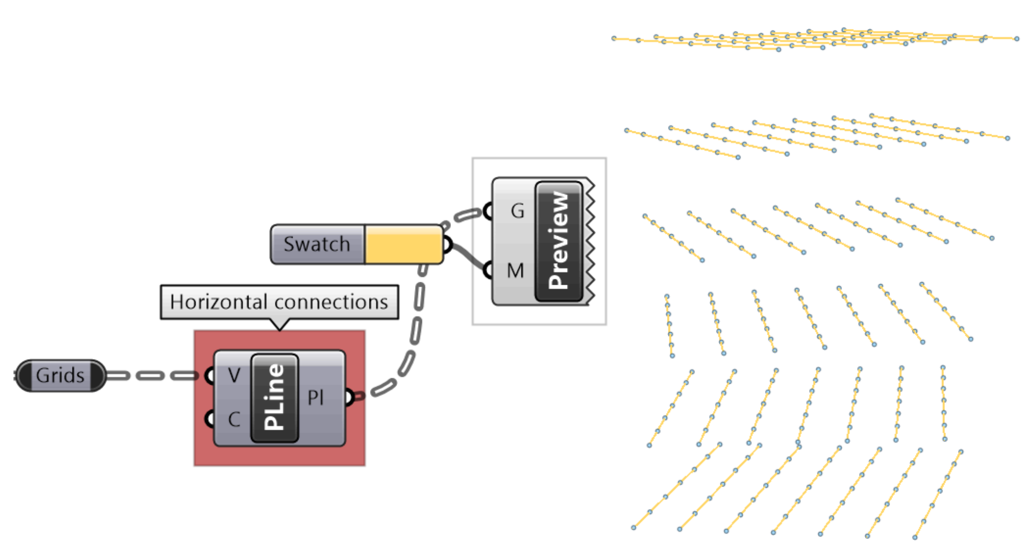
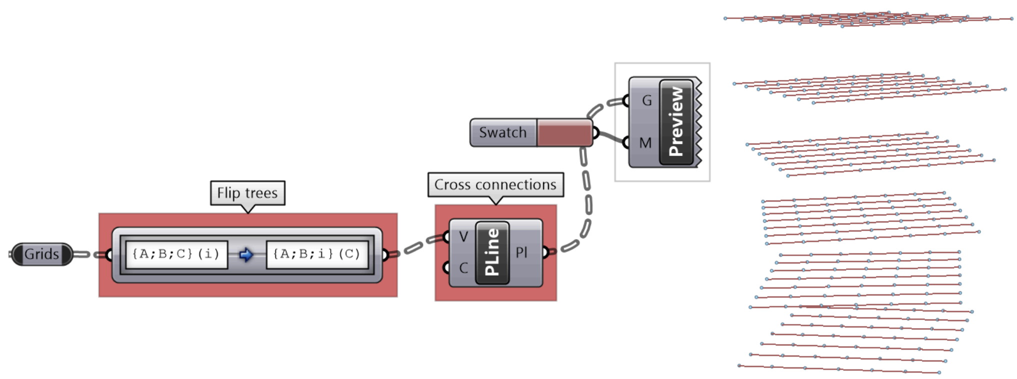
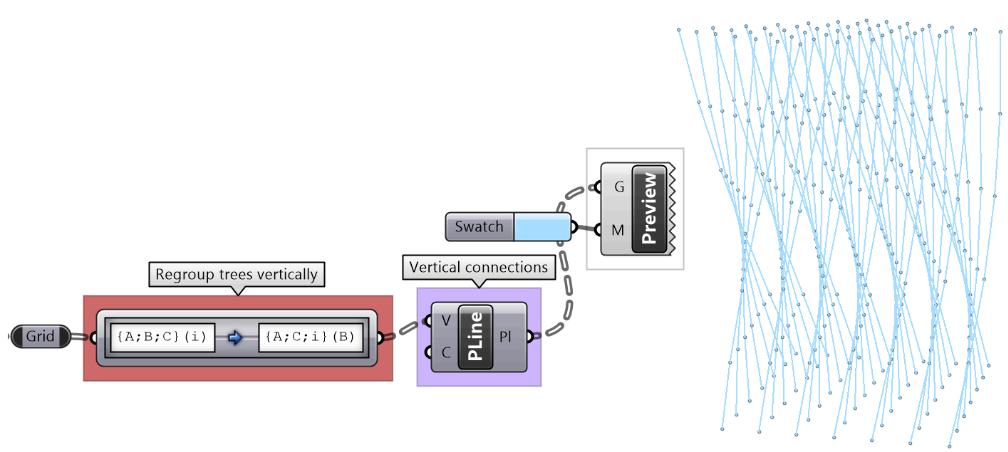
3_6_3_B Building strucuture tutorial

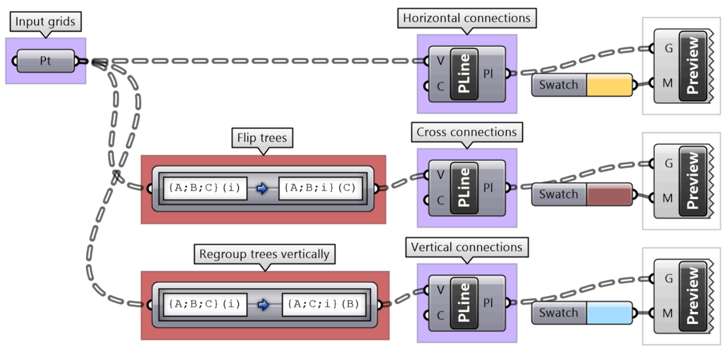
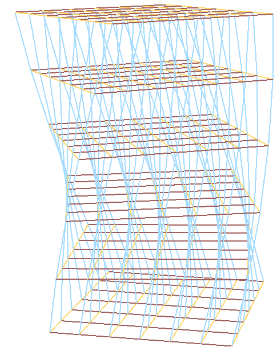
Given the input tree of points, create the following structure.





Solution	
The initial tree has 42 branches, 7 branches in each of the 6 trees	

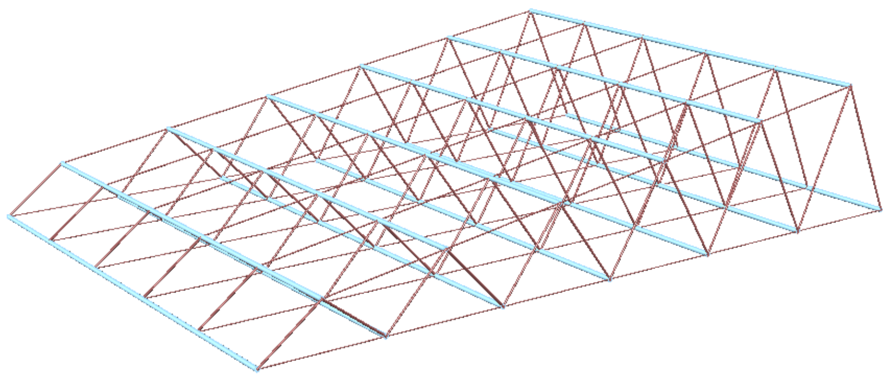
<table>
<tr><td>The Polyline component connects the elements in each branch</td><td>
</td></tr>
<tr><td>Flip the trees using Path Mapper by switching branch and element indices</td><td>
</td></tr>
<tr><td>Regroup the elements of corresponding branches in all trees using the Path Mapper</td><td>
</td></tr>
</table>

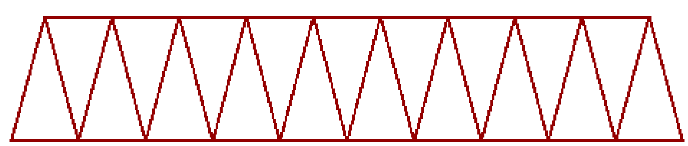
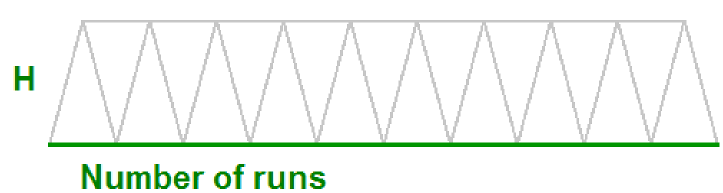
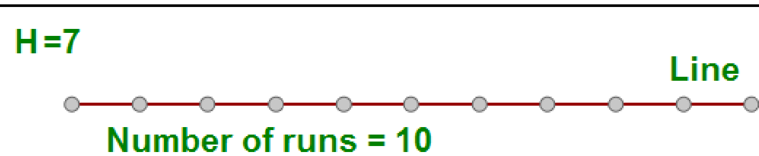
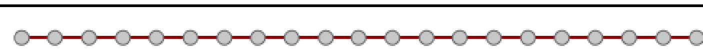
Final result Create all connections	 

3_7: Advanced data structures tutorials

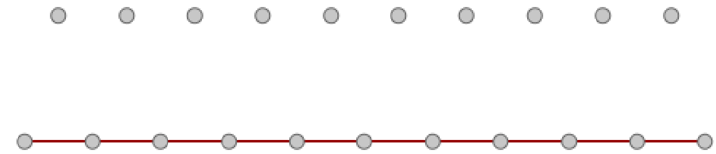
3_7_1: Sloped roof tutorial

Create a parametric truss system that changes gradually in height as shown in the image.

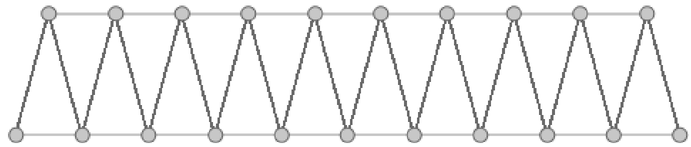


Solution	
Algorithm analysis: First, solve it for one simple truss	
Identify desired output for a single truss	
Define initial input 1- Base line on XY-Plane 2- Number of runs 3- Height	
Algorithms steps:	
Create input (L=line, H=height and R= #runs)	
Divide curve by 2*R	

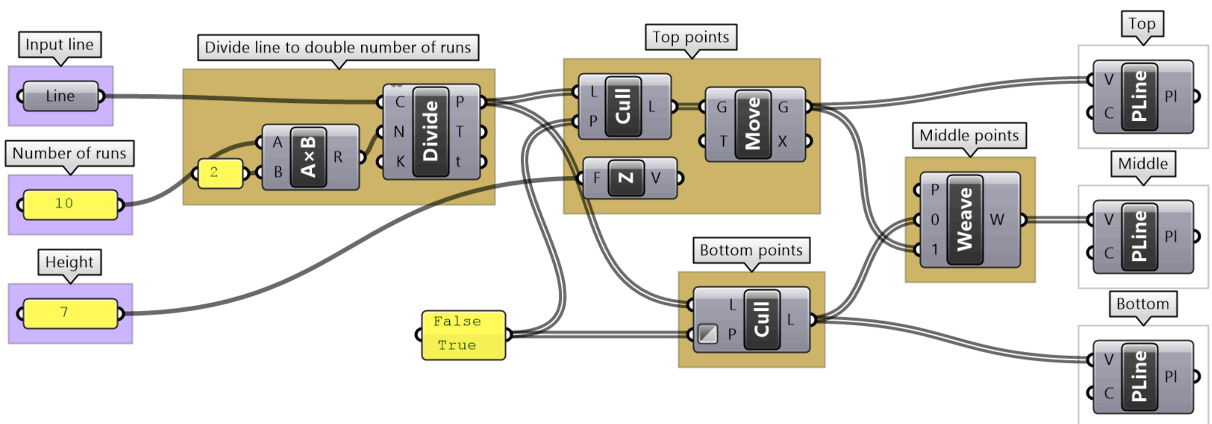
Move every other point in the Z direction by height



Create 3 sets of ordered points for the bottom beams, top beams and middle beams, then connect each of the 3 sets with a polyline

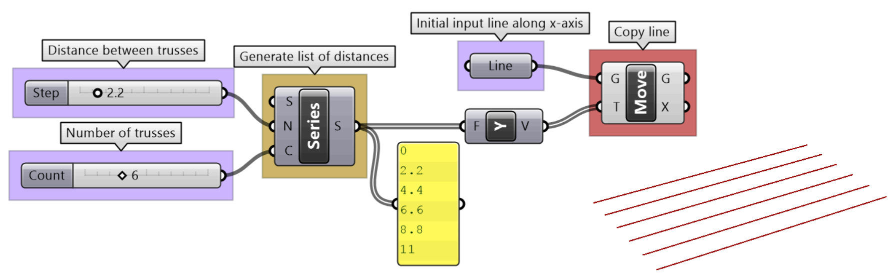


Implement the algorithm for a single truss In Grasshopper



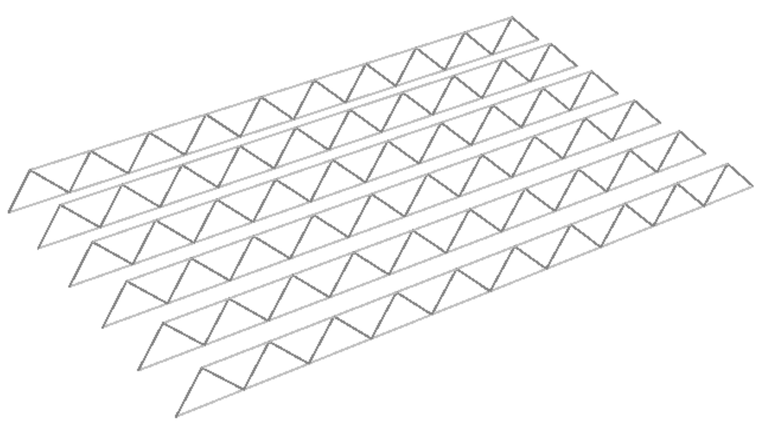
Resolve for multiple trusses with variable height

Create a series of base lines using the initial line and copy in Y-Axis direction

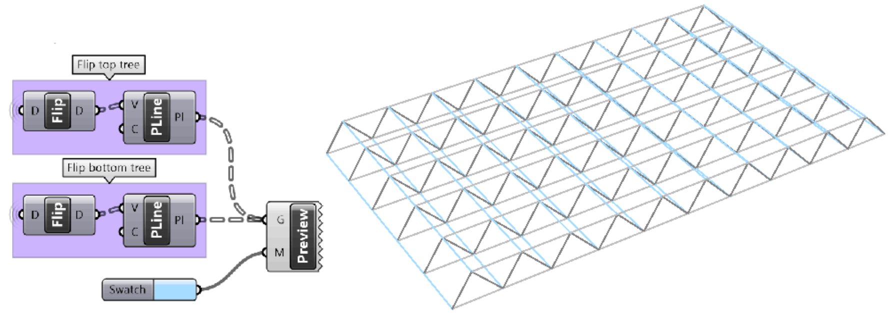


Use the list of lines as input instead of a single line.

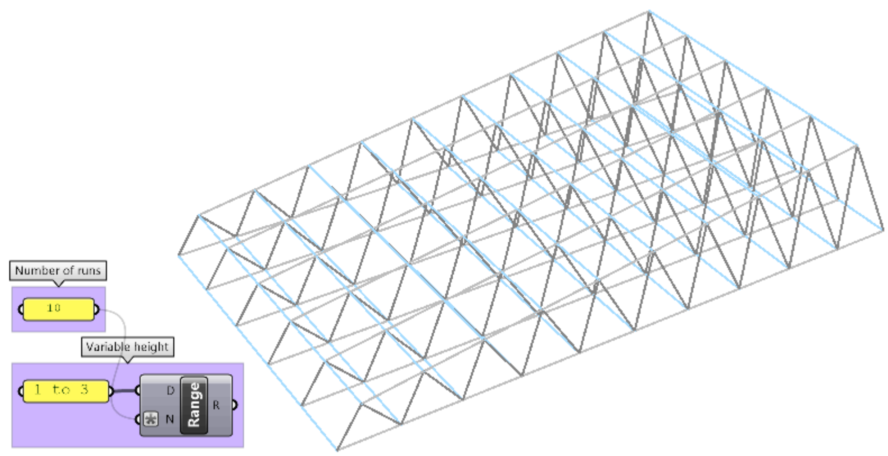
Notice that instead of a list of points for each of the 3 sets (bottom, top and middle), we now have a tree or grid of points with a number of branches equal to the number of trusses



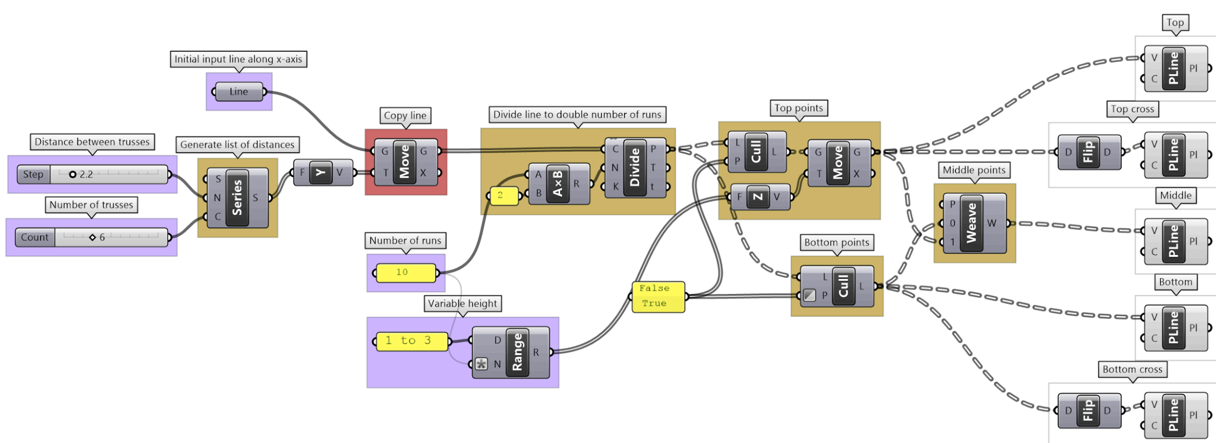
Create cross connections using ***Flip*** tree operation for the bottom and top trees



Create variable height

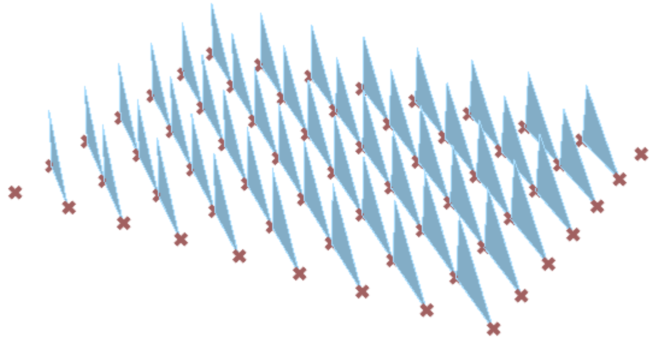


The complete solution implementation in Grasshopper:



3_7_2: Diagonal triangles tutorial

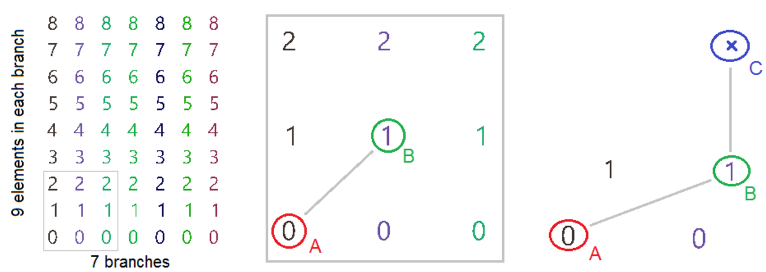
Given the input grid, use the *RelativeItem* component to create diagonal triangles

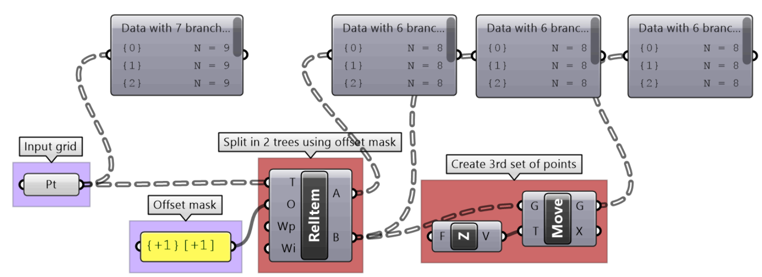


<table>
<tr><th colspan="2">Solution</th></tr>
<tr><th colspan="2">Algorithm analysis</th></tr>
<tr><td>To generate the triangles, we need 3 sets of corner points.

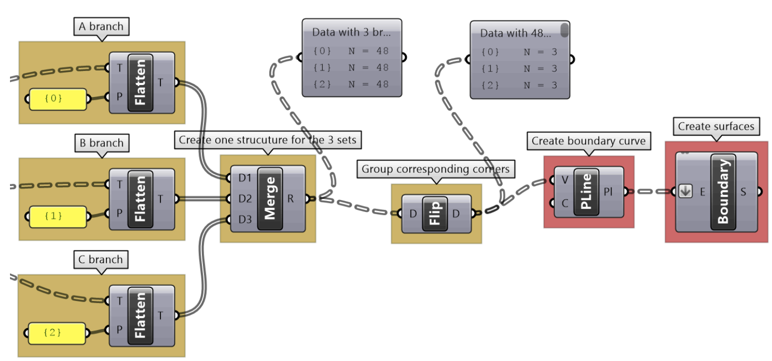
Two of the point sets (A, B) are within the grid. B is diagonal from A (relative index is +1 branch and +1 element)

The third point set (C) is a copy of set (B) moved vertically.

Group corners to connect into boundaries then generate surfaces</td><td>
</td></tr>
<tr><th colspan="2">Grasshopper implementation</th></tr>
<tr><td>Use RelativeItem to create set A and set B (use “{+1}[+1] mask)

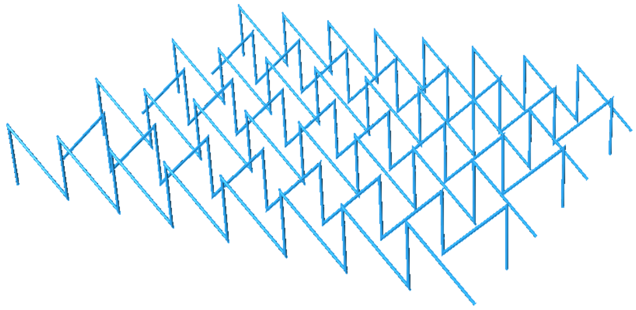
Move set B vertically.</td><td>
</td></tr>
<tr><td>Create a tree with 3 branches for sets A, B and C.

Flip the tree to group corresponding points.

Use Polyline and Boundary to generate the surfaces.</td><td>
</td></tr>
</table>

3_7_3: Zigzag tutorial

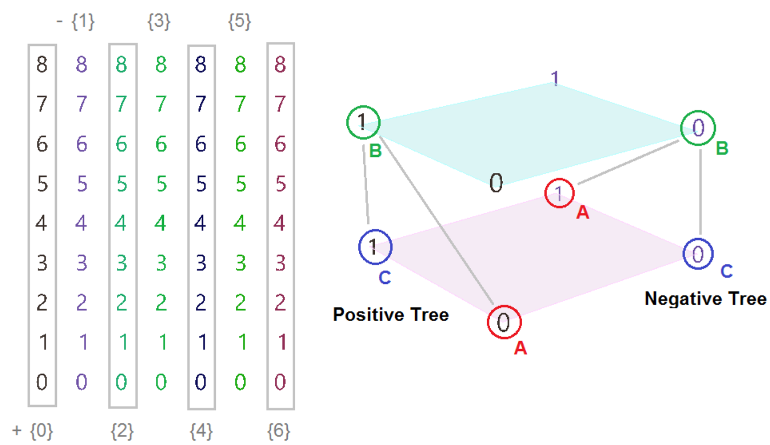
Create the structure shown in the image using a base grid as input.



<table>
<tr><th colspan="2">Algorithm analysis</th></tr>
<tr><td>Since the zigzags alternate directions from one row to the next, it is best to split the grid into 2 parts, positive and negative.

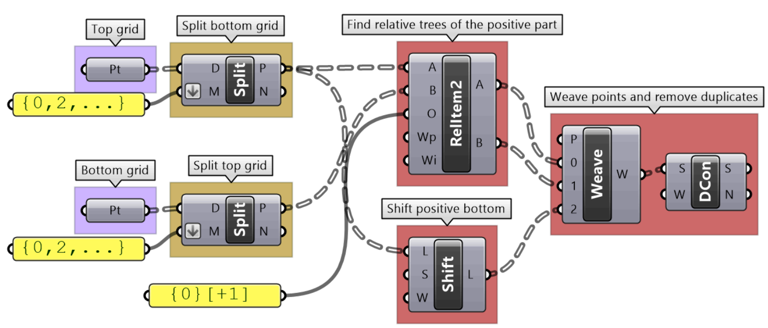
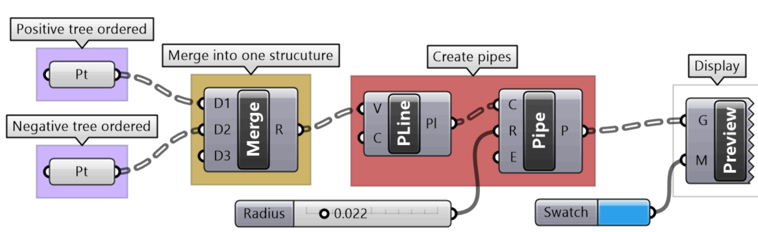
Find 3 sets of points in the positive tree and order

Reverse the elements in the branches of the negative tree, then find the 3 sets of points and order

Merge back the 2 trees to create geometry through points</td><td>
</td></tr>
<tr><th colspan="2">Grasshopper implementation</th></tr>
<tr><td>Use the Split Tree component to generate positive and negative trees for both bottom and top grids. Use {0,2,...} split mask.

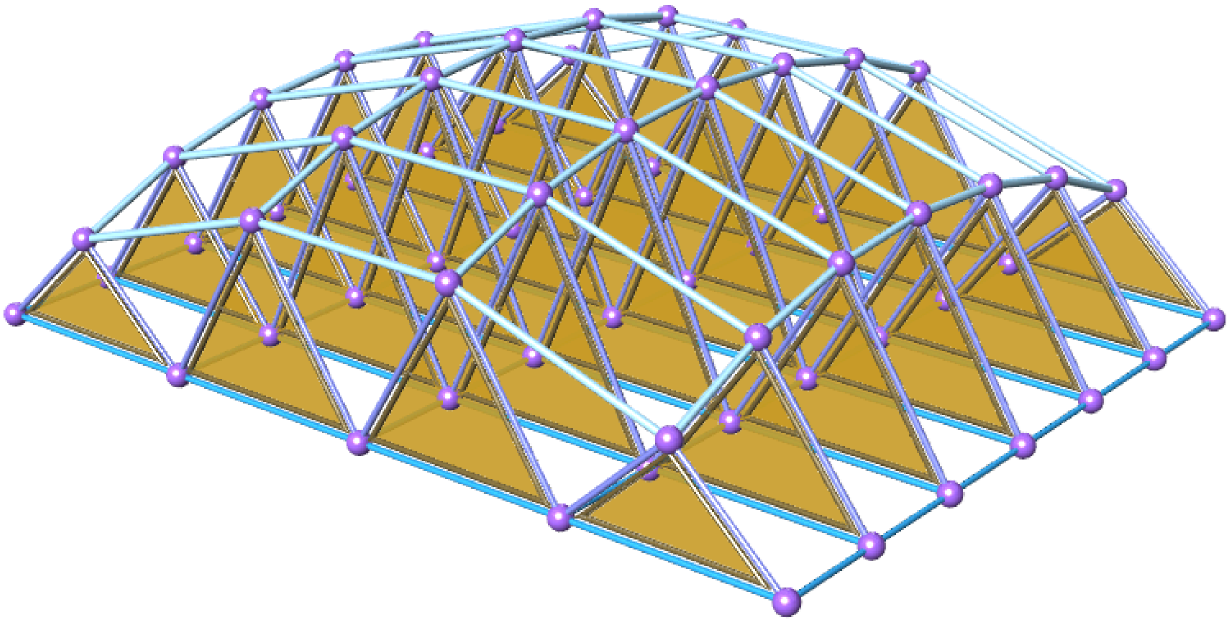
Use RelativeItems2 to create A and B trees, use {0}[+1] relative mask.

Use Shift to create the C tree.

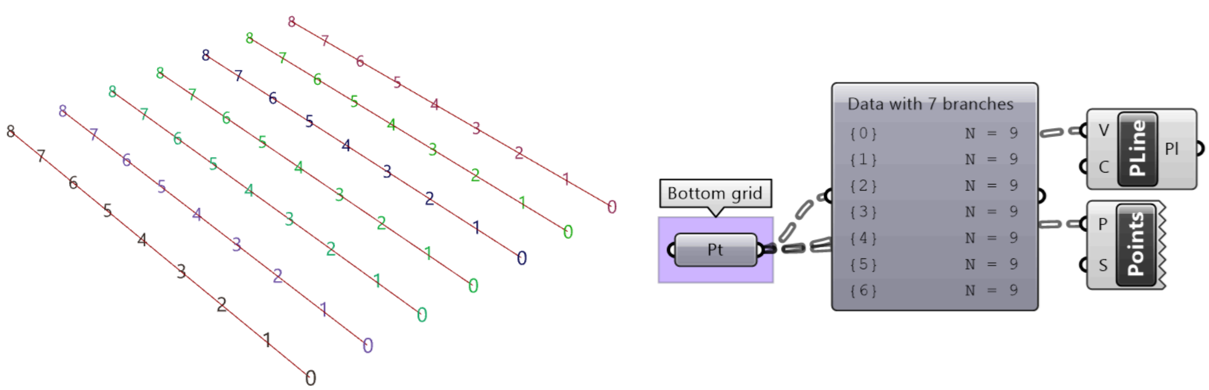
Use Weave to combine data in the intended order, then remove consecutive duplicates using the DCon component.</td><td>
</td></tr>
<tr><td>Merge ordered positive and negative trees to generate geometry using Polyline and Pipe components.</td><td>
</td></tr>
</table>

3_7_4: Truss with plates tutorial

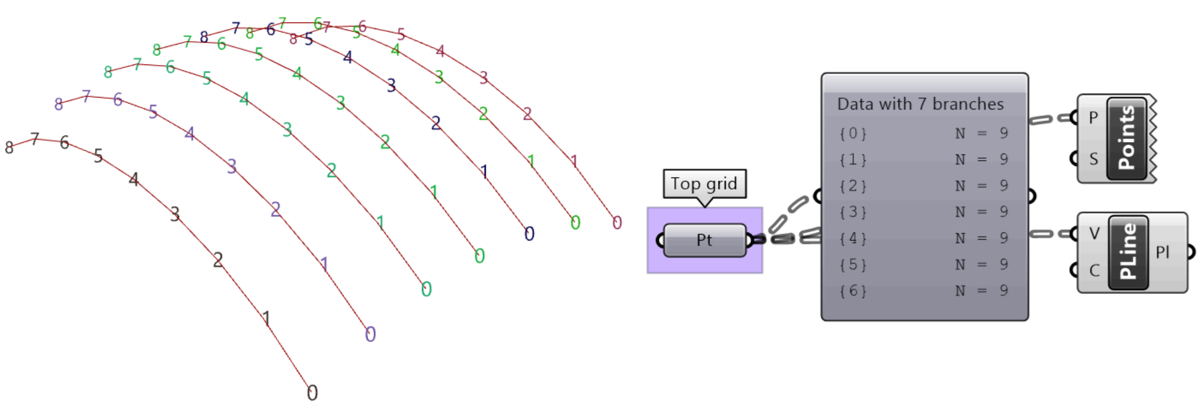
Create the structure shown in the image using a base grid as input:



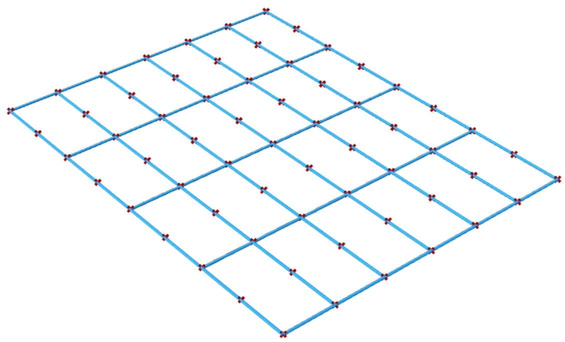
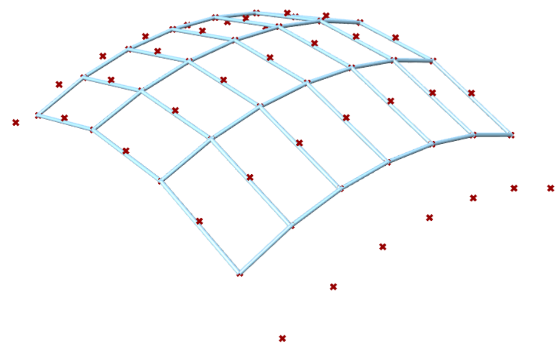
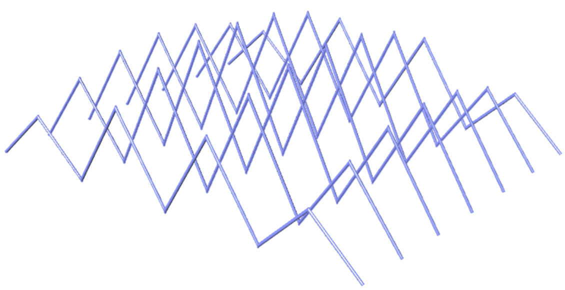
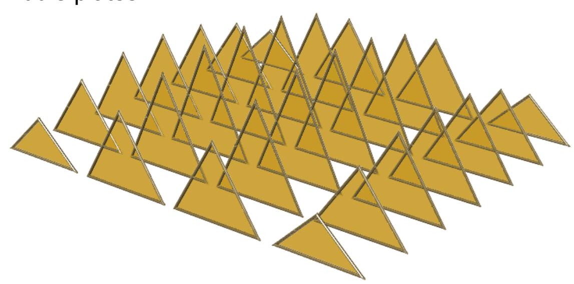
Algorithm analysis
Understanding input: The 2 input grids have a similar data structure of 7 branches and each branch has 9 elements. Bottom grid:



Top grid:



Understanding output: There are 4 parts to the output:

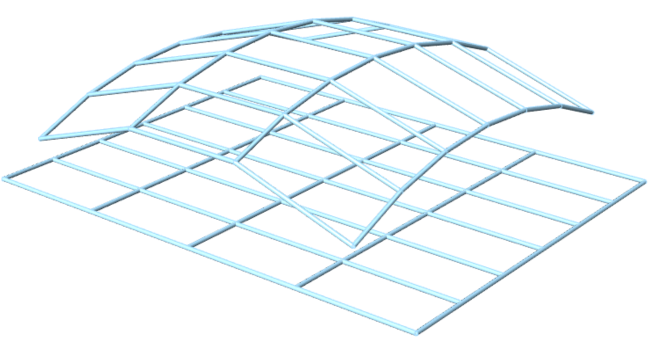
Bottom beams 	Top beams 
Middle beams 	Middle plates 

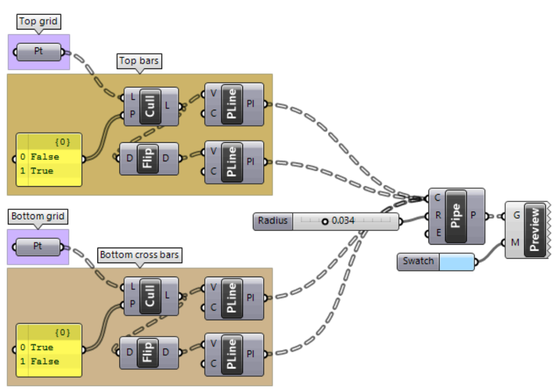
Discussion: Constructing the bottom and top grids can be achieved with culling some points and flipping the points grid to get both directions. The middle beams weave the 2 culled grids of the bottom and top grids. We can also use the culled points to create the joints.

Constructing the triangular connections is more involved since we need to create groups of 3 points that use a pair of consecutive points from the bottom grid and one point from the top. We can use relative trees to solve this. We can then offset the triangles to create the frame points, and offset again to create the plates points.

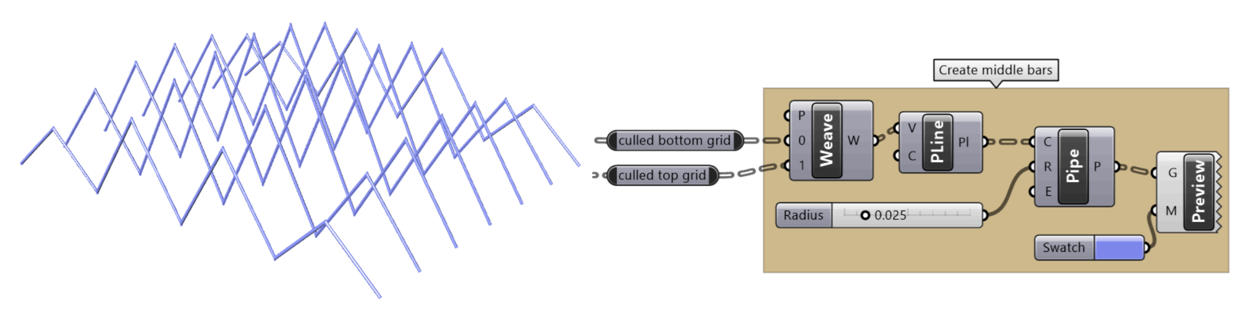
Grasshopper implementation

Cull top and bottom tree, flip culled tree, then feed the 4 trees into a pipe component with the desired radius as a parameter.

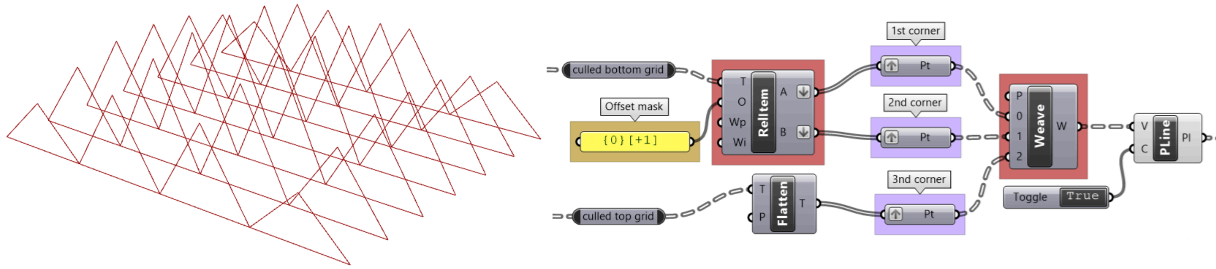




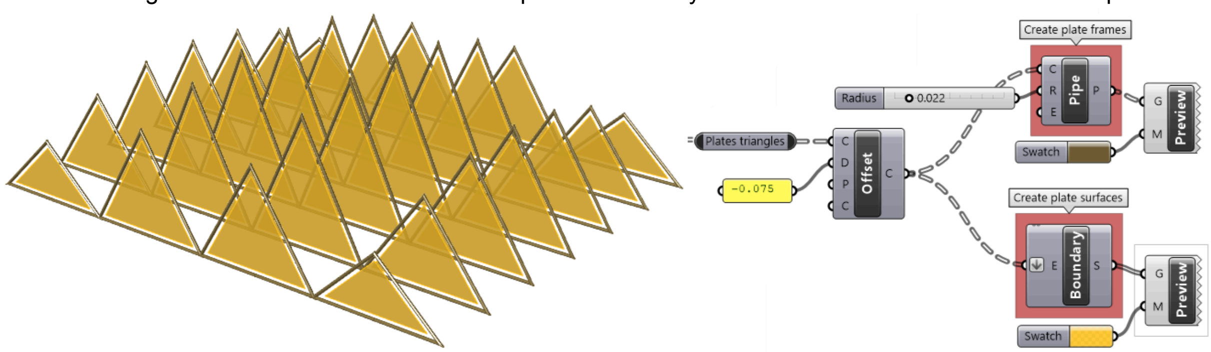
Weave bottom and top grids to generate the grid of middle beams. Connect grid rows with a ***Polyline*** the use ***Pipe*** with the radius as a parameter



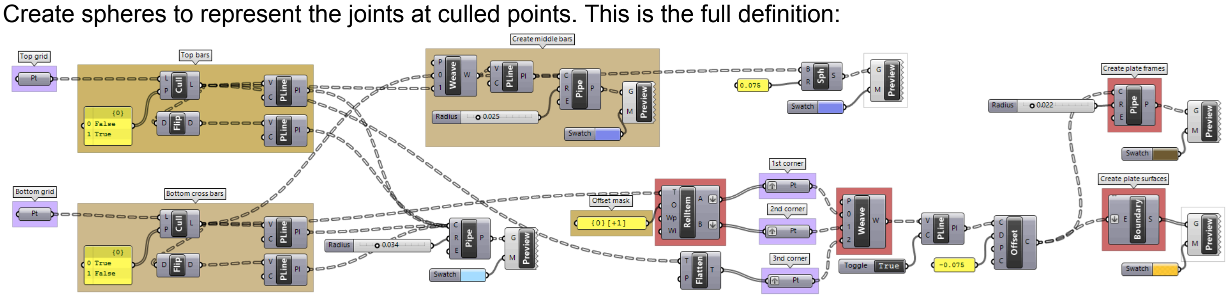
To create the triangular connections, we will use a relative tree on the culled bottom grid, and combine with the culled top grid. Use Offset to generate smaller grid for the plates and their frame



Offset the triangles to create desired sizes. Use Pipe and boundary to create frames and surfaces for the plates.

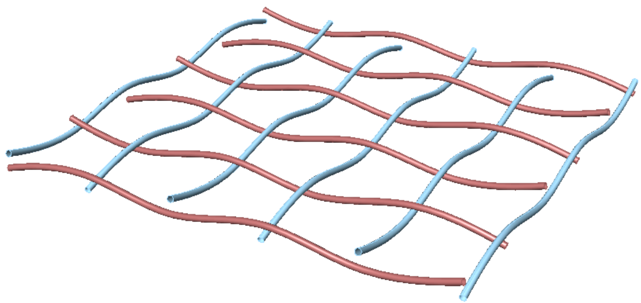


Create spheres to represent the joints at culled points. This is the full definition:



3_7_5: Weaving tutorial

Create flat weaved threads using a rectangular grid as an initial input. Set your desired density and size. Bonus: Make the weaving go along any surface

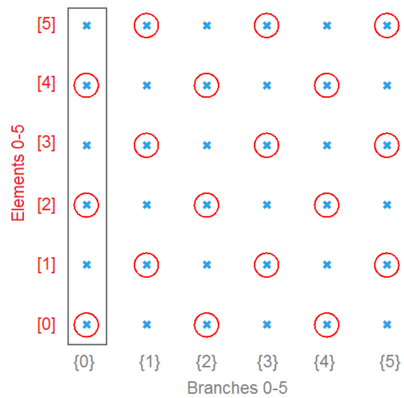


<table>
<tr><th colspan="2">Algorithm analysis</th></tr>
<tr><td>The input is a planar square grid with vertical branches. For vertical threads:

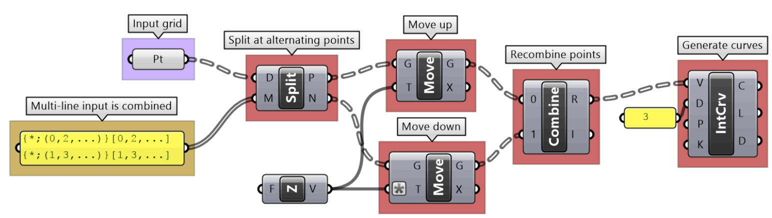
Split the grid into two parts alternating elements in each branch.

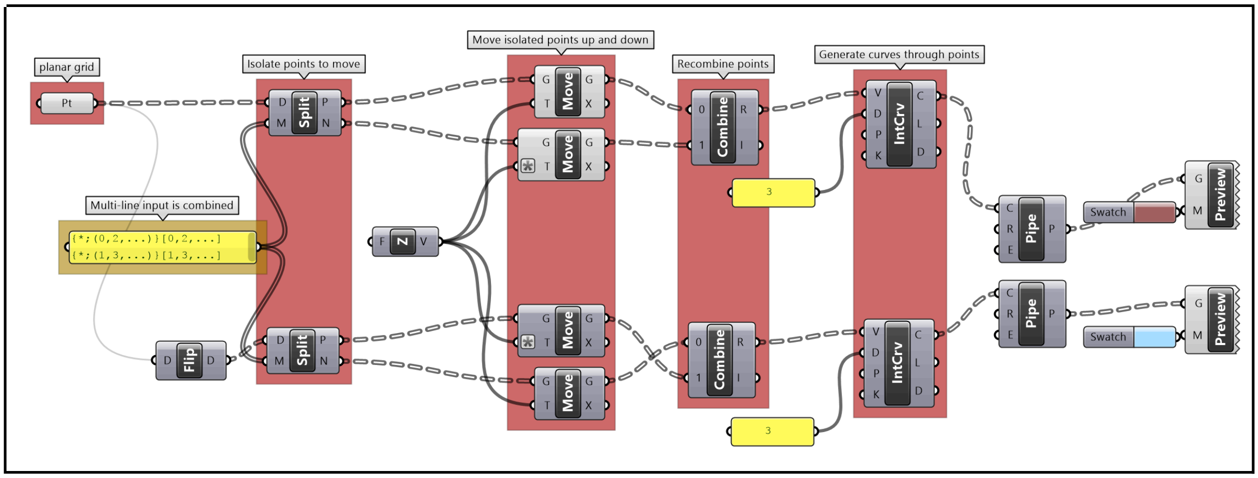
Move the first part up, and the second down, then recombine the parts into one set

Draw a curve through the points in each branch.

Flip the grid, then repeat to create horizontal curves</td><td>
</td></tr>
<tr><th colspan="2">Grasshopper implementation</th></tr>
<tr><td>Use Split Tree to separate alternating points and move up and down

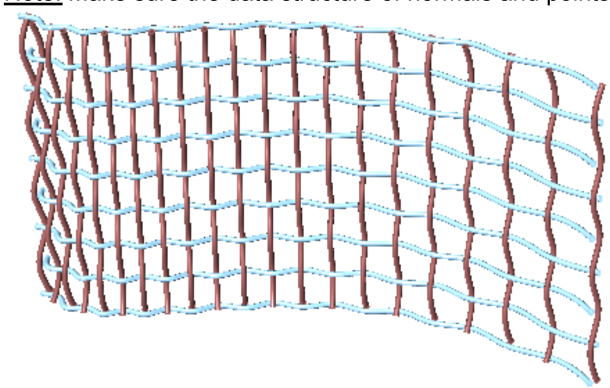
Combine points and use IntCrv to interpolate through points of each branch

Flip the tree, and repeat Split, Combine and IntCrv to create curves in the other direction</td><td>
</td></tr>
<tr><th colspan="2">The full Grasshopper definition</th></tr>
</table>



Expanded solution

Instead of using the Z-Axis to move points up and down, use the surface normal direction at each point
Note: Make sure the data structure of normals and points match



The full Grasshopper definition: