



# Design for interlocking parts

## Innovative designs

### Introduction

This chapter is intended as a design-oriented tool that combines reference, instruction, and inspiration, and should remain relevant as digital manufacturing processes and technologies continue to evolve. Expect to find answers to specific questions and needs, or stumble across something new to try in your digital manufacturing journey.

### Chains

#### Basics

Chains are assemblies of interlocked links. With powder-based 3D printing, these interlocking assemblies can be printed in one go, as long as they are designed with sufficient gaps.

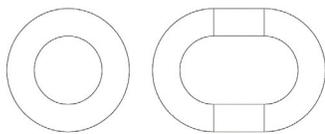


Figure 1: Example of basic links

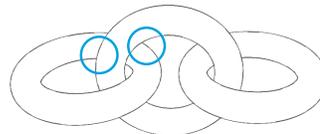


Figure 2: Ensure sufficient gaps to prevent accidental fusing

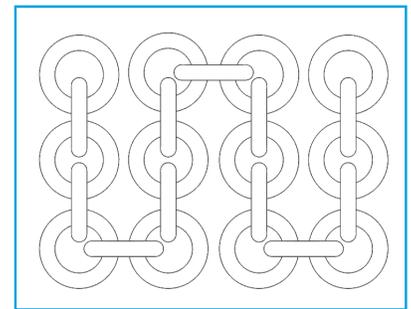


Figure 3: You can also design chains folded for compact packing and for printing parts that are longer than the print bed's dimensions.

#### Modifications

Thanks to 3D printing, links can be infinitely complex. They can be differently shaped, adorned, and even have additional moving parts. You can also blend different kinds of links or change scales.

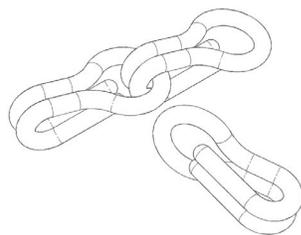


Figure 4: This chain link features an opening, which allows the chain to be re-configured after printing, as needed.

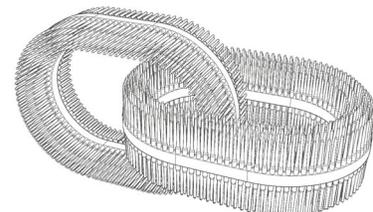


Figure 5: Textures can be added, such as the fur-like surface on the links above.

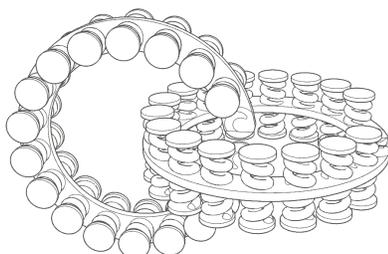


Figure 6: These rings feature both springs for texture and openings for re-configurability.

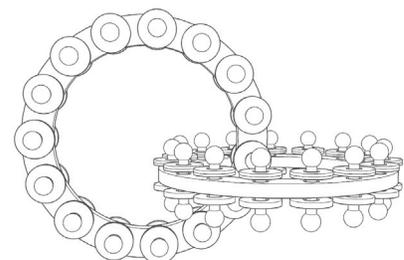


Figure 7: The disks "riveted" on these links add both acoustic and tactile properties.

## Packing chains

### Orientation

To avoid vertical and horizontal links, which can be cosmetically (and perhaps mechanically) different, print the chain with each link at a 45-degree angle to the print bed, alternating between -45 and +45 degrees with respect to the vertical direction.



Figure 8: Chain links oriented at 0 and 90 degrees to the print bed



Figure 9: Chain links oriented at -45 and +45 degrees to the print bed

### Packing

Some chains are too long to fit in one layer of the print bed. One option is to print them in layers and then use one or more vertical links to connect the last link of a layer to the start of the one above. However, to avoid having any links (the vertical links) that look different from the others, print the chains in coiled cylinders, as shown to the left.

Start with the links at 45 degrees to the print bed and then angle each link slightly in vertical and horizontal directions. This is more easily achieved via scripting than laying out the chain by hand, but it can be done either way.

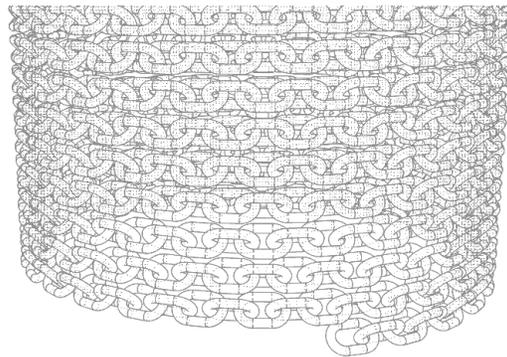


Figure 10: The bottom of a cylinder containing a chain more than 40 feet long

### Measuring printed length

Note that the printed length of the chain will be longer than its apparent length in the model to be printed since the links must not touch each other while printing. The length of the final chain can be calculated as shown below. Designers may need to take this kind of expansion into account for more complicated interlocking designs like chainmail.



$$\text{Printed Length} = (\text{number}_{\text{of links}} \times \text{length}_{\text{of link}}) - (\text{number}_{\text{of links}} - 1) \times (2 \times \text{thickness}_{\text{of links}})$$

If the chain is attached to something using its first and last links, subtract another two more thicknesses of link.

## Chainmail

### Basics

Chainmail is a basic textile-like structure that can be made from interlocked chain links. With 3D printing, entire sheets can be printed at once. They can also be printed and folded to be larger than the print bed.

A basic four-in-one chainmail features four rings interlocking into every one, but there are many different varieties of chainmail.

An excellent resource for further tutorials is <http://www.maillageartisans.org/>.

### How-to

For every individual ring, four other rings intersect. Ensure there are sufficient gaps, so that none of the four rings intersect with either the base ring or each other.

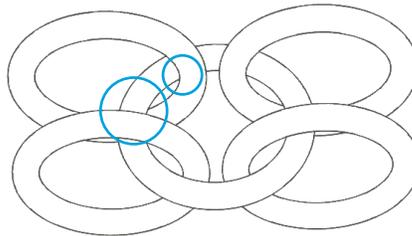


Figure 11: Ensure sufficient gaps to prevent accidental fusing

These units can be repeated in rows. In this particular example, the rings are rotated to create a 90-degree angle with one another, as each row is alternatively rotated 45 degrees clockwise or counterclockwise. However, this angle can be increased or decreased according to the design.

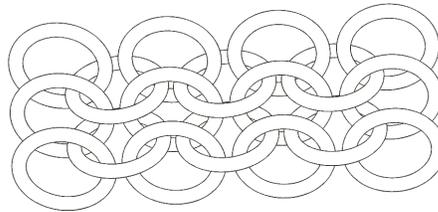


Figure 12: Chainmail design example

### Modifications

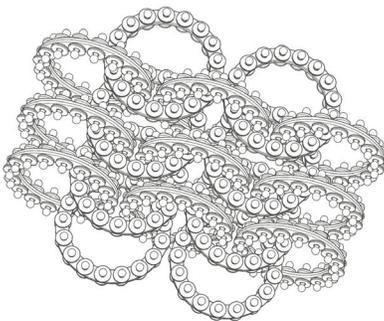


Figure 13: The “riveted” disks from the chains example also work well for chainmail.

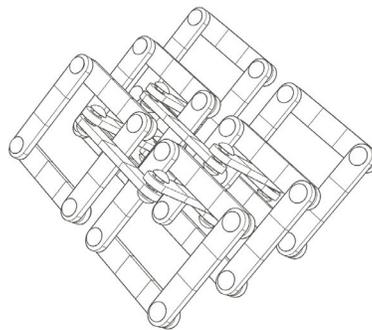


Figure 14: These hinged diamonds result in a chainmail with additional expanding properties at the link level.

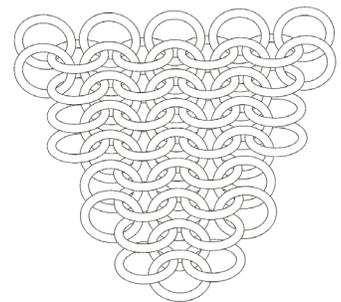


Figure 15: Chainmail pieces can also be trimmed and shaped in CAD, prior to printing.

## Beyond four-in-one

3D printing makes it easier to create interlocking pieces that use more than just circles or ellipses. The following example interlocks flowers with ellipses, but you can create intricate fabrics of unlimited designs.

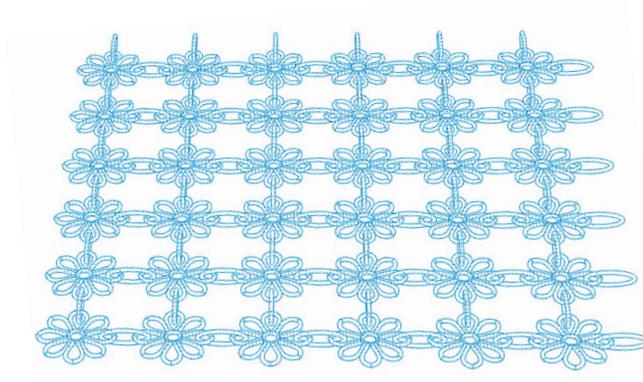


Figure 16: Chainmail design interlocking flowers with ellipses

The chainmail to the right consists of stars and two sizes of circles. The small circles connect the stars to the big circles. Note that the big circles are laid out below the stars for a more compact print job and to avoid accidental fusing. This uses a hexagonal linking pattern.

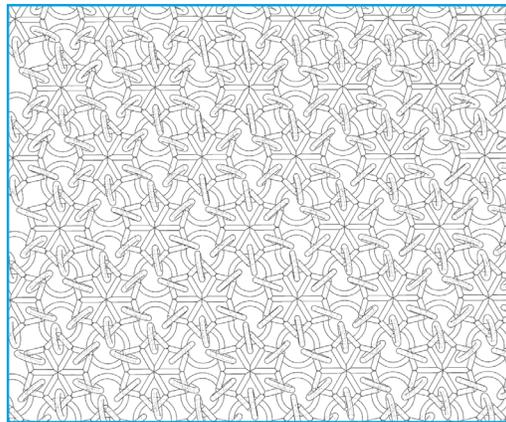


Figure 17: Chainmail design interlocking stars with circles of two different sizes

## Printed examples



Figure 18: Starry chainmail

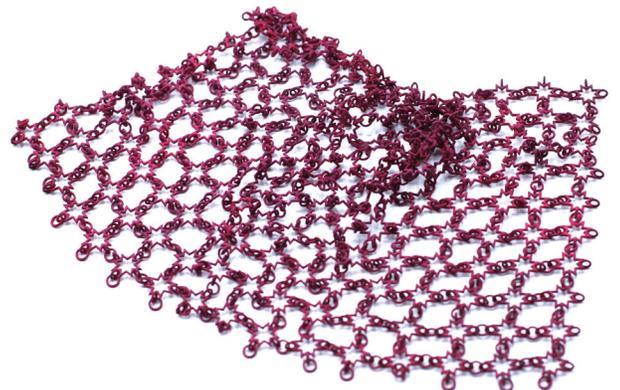


Figure 19: Star fabric

## Quad-based “fabric”

### Base elements

This design draws inspiration from metal fabrics, like those found in some vintage handbags. There are two base elements to this structure:

- A ring (can be a torus, extruded circle, or even octagon)
- A platform unit with four “legs.” In the example shown, the legs taper inward and emerge from a flat octagonal base.

Make sure there is a large enough gap between elements on all sides to prevent them from fusing together.

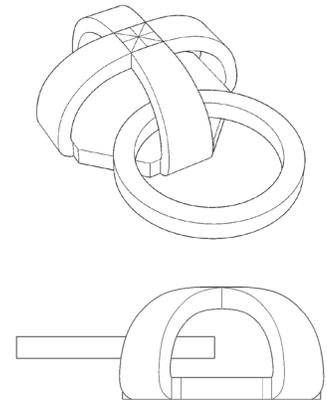


Figure 20: If your elements are too thin, they may print successfully but will fall apart in sandblasting!

### Scaling

Each ring connects to four platform units, and each platform unit holds four rings. The swatch can be repeated as much as you want (or as much as will fit in your print bed). The design can also be printed folded over.

Make sure there is sufficient spacing between the elements. The proportion of ring size to platform unit size will also dictate the visual quality of the mesh and warrants experimentation.

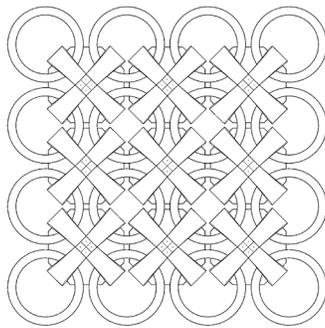


Figure 21: Connection between quad-based “fabric” elements

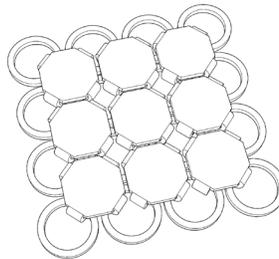


Figure 22: A quad-based “fabric” example

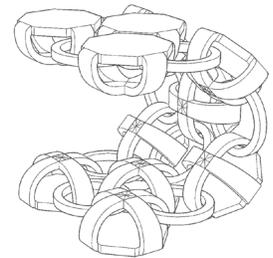


Figure 23: The folded elements shown here are bent 45, 90, and 135 degrees.

### Variations

3D printing means there’s no reason the platform unit has to be flat. Here are some examples of alternative surfaces.

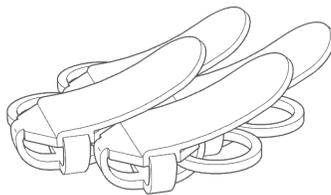


Figure 24: A layered wave pattern obscures the gaps between units.

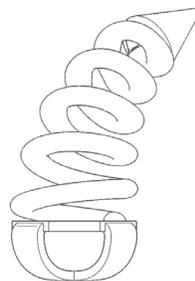


Figure 25: Springs result in novel textures.

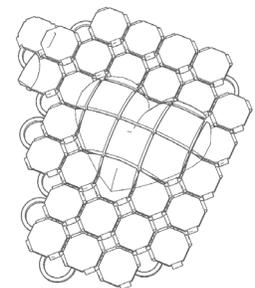


Figure 26: Create “pixelated” 3D images along the surface.

## Single link mesh

### How-to

3D printing allows for the combination and simplification of forms.

For example, a singular unit of angled rings can result in a single shape that can be arrayed to create a mesh.

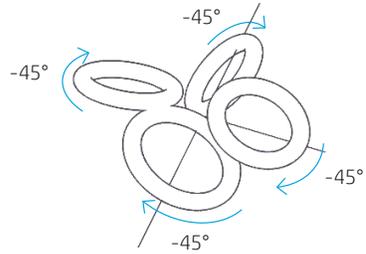


Figure 27: Angled rings resulting in a single shape

However, the shape also can be combined and reduced, only retaining the critical angles for proper interlocking.

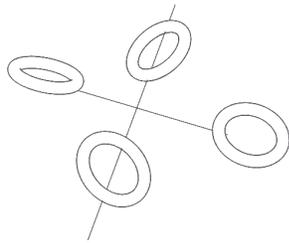


Figure 28: Angled and reduced rings

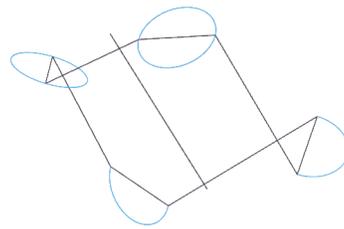


Figure 29: Angled and reduced rings resulting in a single shape

The optimized unit uses less material and looks more continuous.

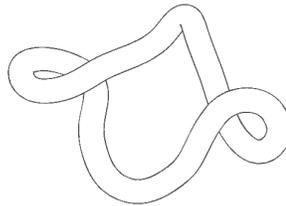


Figure 30: Optimized unit from angled and reduced rings

### Example results

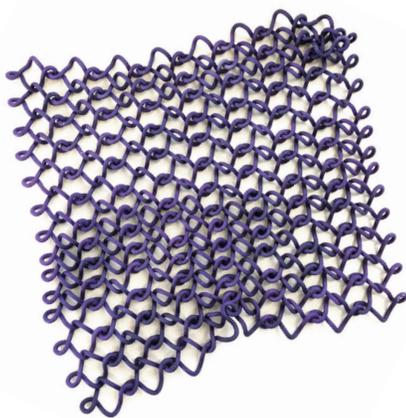


Figure 31: This design also allows for tighter vertical compression, allowing larger sheets to be printed.

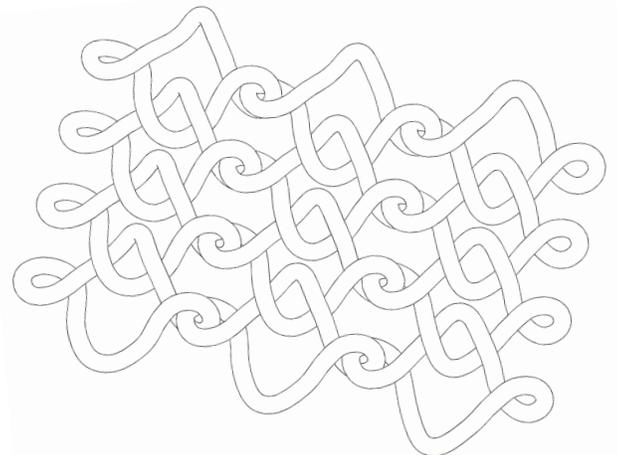


Figure 32: Design of a single link mesh

## Six-in-one weave chainmail

### Basics

A six-in-one weave is slightly stiffer than a four-in-one weave, and grows in a radial fashion more easily than the preceding quad-based chainmails and meshes. Generally, this weave is made of two sizes of rings, with six smaller rings fitting into one larger one.

The rings do not necessarily have to be circular. Also, the example link shown features six spokes separating the rings. However, this is a stylistic and optional choice.

Each smaller ring connects two larger ones. The increased number of connection links causes the structure to somewhat resist folding, though it is still flexible and movable.

You can also experiment with this type of interlocking design with more or fewer connection links, instead of six, to modify stiffness.

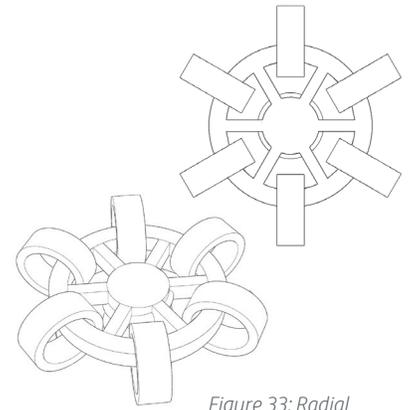


Figure 33: Radial growth design

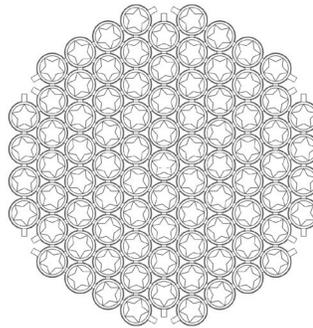


Figure 34: An example of a six-in-one weave chainmail

### Modifications and applications

The flat plane provided by the larger rings provides an opportunity for developing more advanced structures.

In this example link, the spokes support a decorative panel on a flexible spring. The decorative panel gives the weave a more solid look, while the spring provides texture.

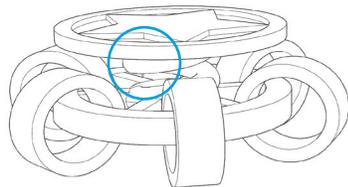


Figure 35: Make sure that any additional structures have sufficient clearance from the rings.

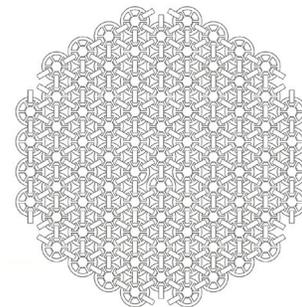


Figure 36: An advanced six-in-one weave chainmail

One example application benefiting from this structure's radial nature is a bucket hat.

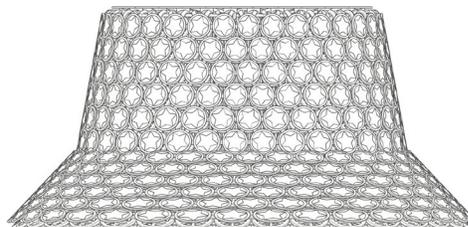


Figure 37: Bucket hat design

## Hexagon-based “fabric”

### A different kind of drape

As long as the elements can be easily tiled, different types of grids like this one are possible. This example uses a “sandwich” of hexagons connected by posts and linked together with triangles that circle around posts. This creates a fabric with no “wrong” side.

Hexagonal grids provide more degrees of freedom for draping compared to the quad fabrics shown before, but the use of posts here instead of the arches in the quad example can lead to a stiffer fabric if the posts are not tall enough to provide much movement.

We can easily adjust the flexibility, drape, sturdiness, weight, and other parameters of the fabric by varying the thickness of the hexagons, the height of the posts connecting the hexagons, the size of the triangle connectors, and so forth. The example fabric shown also has holes in the center of the hexagons to make it easier to clean via sandblasting.

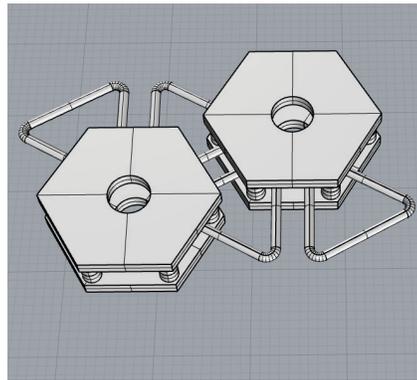


Figure 38: More information on these hexagonal units is available on the next page.

### Creating larger sheets

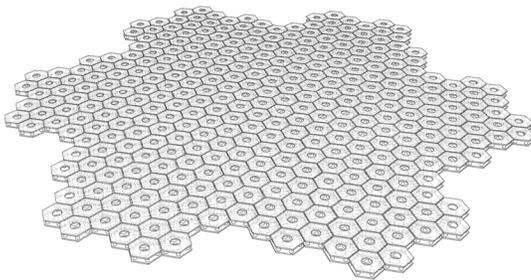


Figure 39: Hexagonal fabrics can be thought of as polar arrays instead of grids, leading to snowflake-like shapes.

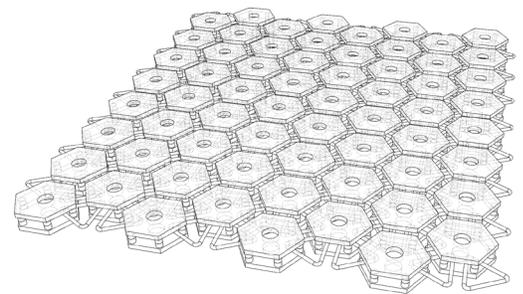


Figure 40: The easiest tiling unit to use, which is mentioned on the next page, naturally leads to offset rows and columns.

## Tiling units

### General considerations

For chainmail and fabric swatches, and even 3D cuboid structures, we design a “tiling unit” to lay out along one (as in a chain), two, or three dimensions. The tiling unit has connectors at the edges for the directions along which we want to tile it.

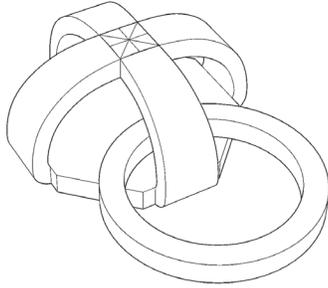


Figure 41: The quad fabric's tiling unit consists of a square with legs and a connector on the bottom right edge.

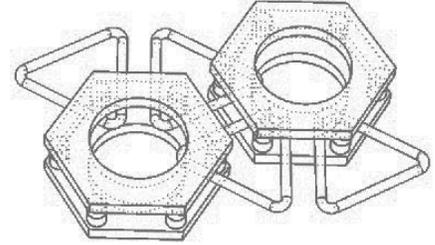


Figure 42: The hexagonal fabric uses a tiling unit consisting of a base hexagon with another one rotated to its upper right side. There are two connectors on the top of the base hexagon, and two on the bottom of the rotated hexagon.

Tiling units lend themselves to an array of functions in CAD design tools, and especially to scripting. We just determine the space we want between the units so they connect well and do not accidentally fuse. The other parameter is the number of units along the dimensions we want to tile.

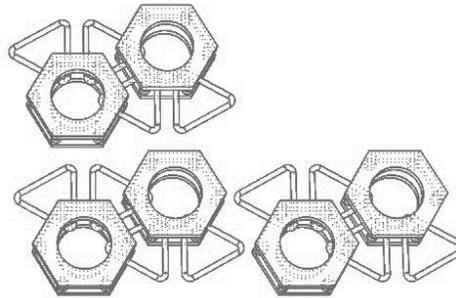


Figure 43: This example shows the hexagonal tiles in X and Y directions pulled away from each other so we can see how they connect.

### Layering

3D printing allows us to combine techniques and create fabrics with several layers. This offers a great deal of room for experimentation.



Figure 44: This example uses a quad fabric with embossed flowers and a second layer of chains and logos.

## Applying interlocking swatches

### Trimming

Sheets can be trimmed in CAD prior to printing to create the desired final outcomes. This is much less wasteful than printing full sheets and editing them after.

Sheets can also be folded to create larger parts, like in this shirt example.

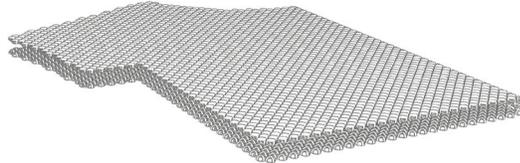


Figure 45: A shirt designed from folded sheets

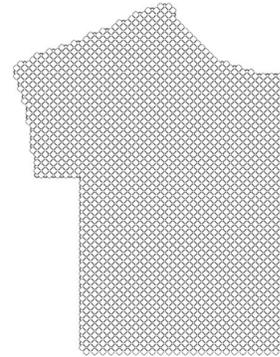


Figure 46: Top view of a shirt design

### Seaming

You can design in edges to your interlocking structures by combining sheet-like structures with chain structures. Adding this border cleans up the edges.

Doing so also creates an easier, more aesthetically pleasing way to connect separate parts. For example, the skirt panel on the left can be combined with four others, with ribbon woven through the chain trim, to make a final design.

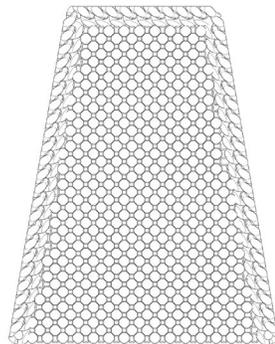


Figure 47: Sheet-like structures combined with chain structures

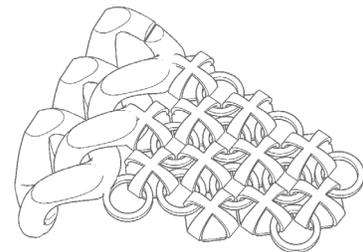


Figure 48: Edge detail

### Stretching

Interlocking structure designs can also be stretched and deformed to fill in the desired shape. However, be sure to double check that the transformation does not reduce the clearance between parts too much for successful printing.



Figure 47: Bucket hat design with stretched and deformed interlocking structures

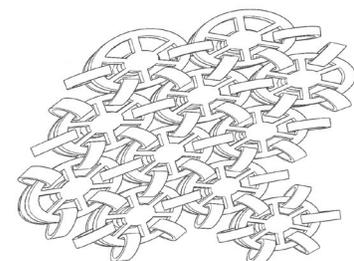


Figure 48: Design detail

## Case study : 3D printed skirt

### Context

Textiles have been refined over centuries of innovation, so 3D printing will likely not replace our standard daily clothing. However, in certain contexts, like the fashion-forward, open desert music festival of Coachella, an easy-to-clean plastic skirt fits right in and makes good sense.

### Overall design

This skirt uses a large-grain version of the Quad-Based Mesh structure. The larger size, with 1.2 mm-thick rings holding 10 mm-wide platform units together, is robust enough to hold up, even when coming into contact with a rough dusty field. The mesh is still fine enough to create natural and comfortable movement.

### Design optimization

Given HP MJF's efficient XY speed, connecting flat panels is the most efficient approach to creating the skirt. The panels were tapered to create a basic, flattering, five-panel skirt. Each panel was then lined with a thicker, twisted chain to create smooth edges and easy attachment points for final assembly.

Ribbons are woven through the chains to stitch the panels to each other. One final ribbon is threaded along the top edges. Due to the chains' compressive qualities, this ribbon helps create an adjustable waistband.

After days of wear at Coachella, the skirt was simply rinsed off with a hose and brought back to HP Labs, where it now resides in the Immersive Experiences Lab's Living Room Lab.

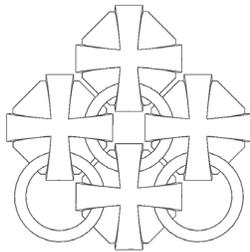
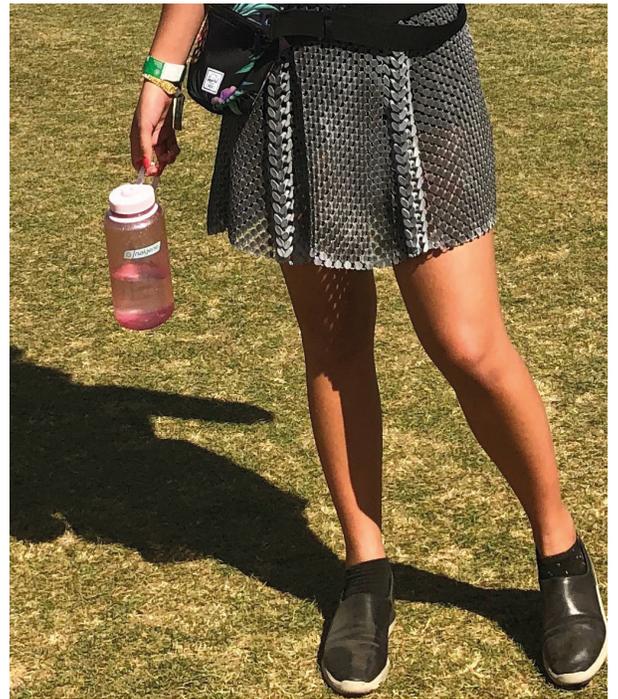


Figure 49: Design detail

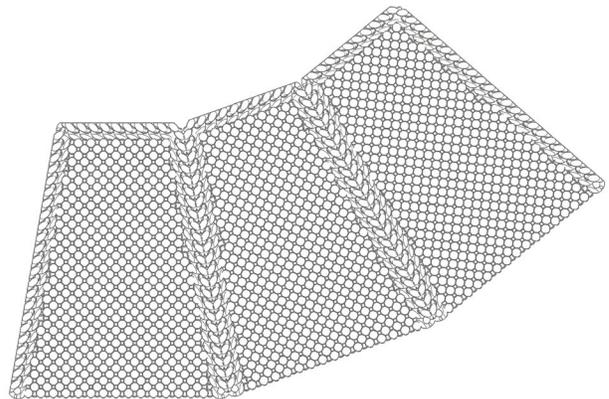


Figure 50: 3D printed skirt design

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