3D printing and data visualisation:
A technology briefing

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These slides online here: http://paulbourke.net/3dprint2014/

http://dha2014.org
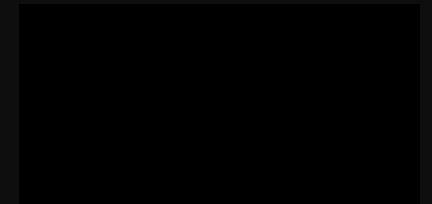
Workshop – Automated 3D Model Reconstruction from Photographs

Steven Micklethwaite, Hasnain Ali Bangash, Centre for Exploration Targeting

Contents

- Motivation, History, Focus

- Hardware
  - Printer types
  - Limitations: Material, colour - strength - accuracy - surface finish

- Suppliers, costs, buy or use a bureau?

- File formats: stl, 3ds, vrml, dae, obj

- Geometry
  - Creating lines / curves
  - Thickening surfaces
  - Manifold surfaces
  - Minimising volume

- Software: Meshlab, Netfabb, Blender

- Questions and examples: Paul Bourke - Andrew Squelch

Motivation

- Definition: Visualisation is the process of applying computer graphics to data in order to provide insight into the underlying structures, relationships and processes.

- While it largely uses the sense of vision, what about the other senses.

- Sonification is visualisation based upon audio, e.g.: Geiger counter, hospital machine that goes "ping".

- Haptics and force feedback uses the sense of touch to "feel" data or processes.

- Tactile visualisation uses the sense of touch, used here in the context of touching physical models.

- Claim: Insight into the geometry / structure of an object can be assisted if we studying it in the same way as we explore objects in real life.

- Benefits also in conveying geometric properties of data in education, public outreach and to peers.

History

- 3D printing generally refers to additive processes where successive layers are laid down to form the model.

- Distinct from computer controlled milling or lathes (and others) where material is removed.

- People tend to imagine it is a recent technology, my first 3D prints were done in 1992.

- First units built as far back as the early 1980s, largely for rapid prototyping in the machining industry, e.g.: prototyping car parts, product design. [Gear example]

- In the 90s it was used for medical prosthetic and implant design and surgery planning, e.g.: brain surgery.

- Stereolithography was coined in 1984 for the process of forming objects from cross-sectional slices. Pretty much everything from now on is going to involve laying down essentially contour layers, building the model in layers from the base upwards.

- Most common printer in the 90s used a liquid photo-reactive resin that solidified on contact with UV laser light. [See ear model].

Focus

- Will limit the discussion mainly to data visualisation, that is, representing data as solid / physical objects.

- Creating models by hand in some 3D modelling package is easier, one simply chooses a package that exports the data in a suitable formats: STL, X3d (see later). Models created with a knowledge of the printing process in mind.

- Some data visualisation packages also export suitable formats, others don't. May need to convert between file formats.

- Some data visualisation packages may provide suitable export formats but the underlying geometry may be unsuited to 3D printing, e.g.: structures too thin (See later).

- Exporting to suitable file formats to support 3D printing may be added to ones existing code base.

- Examples from molecular software (VMD, PyMol)
http://paulbourke.net/miscellaneous/molecular_rp/
Example from rock art reconstruction
http://paulbourke.net/miscellaneous/rapidproto/
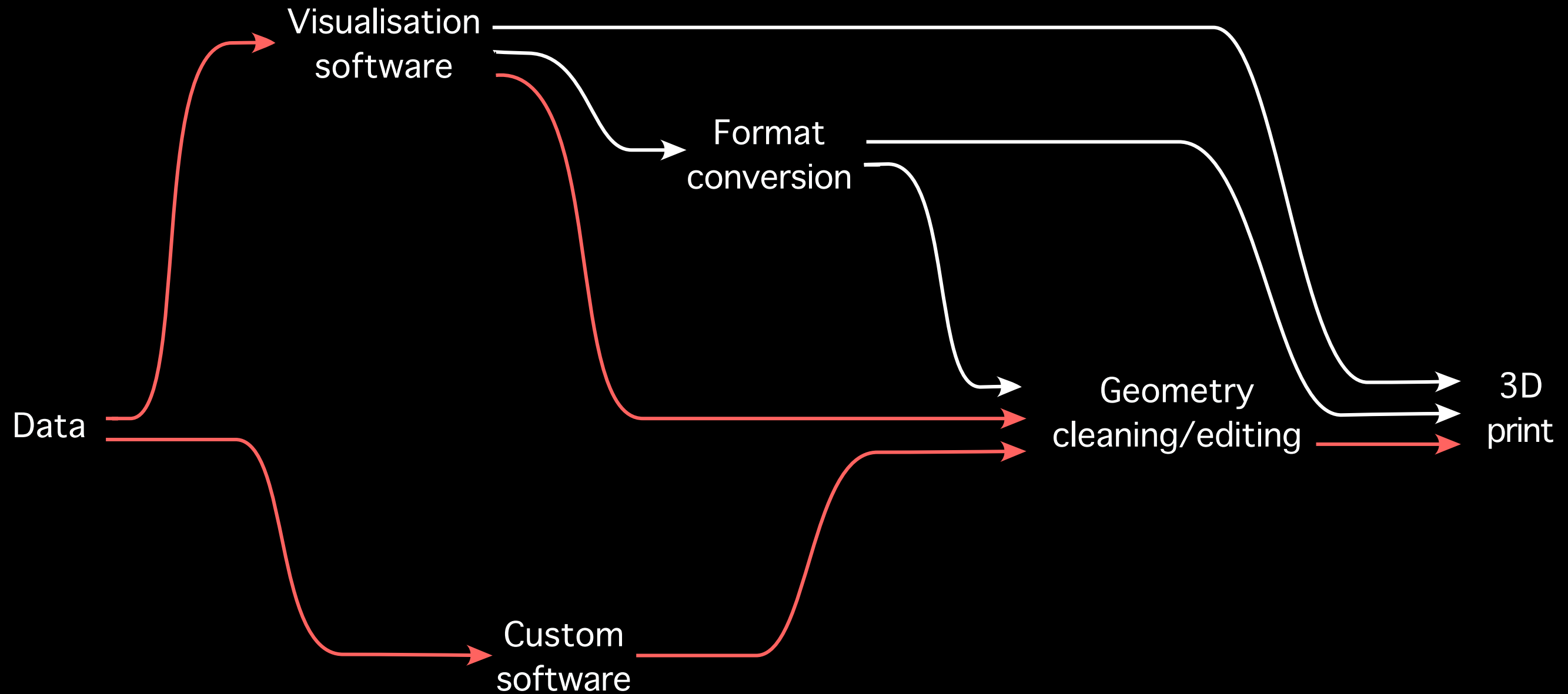
Workflow

Red shows the most common workflows in my experience.

Hardware

- Wide range of technologies
  - FDM: Fused deposition modelling
  - EBF: Electron beam freeform fabrication
  - DMLS: Direct metal laser sintering
  - EBM: Electron Beam melting
  - SLM: Selective laser melting
  - SHS: Selective heat sintering
  - SLS: Selective laser sintering
  - PP: Plaster-based 3D printing
  - LOM: Laminated object manufacturing
  - SLA: Stereolithography
  - DLP: Digital light processing

- Will focus only on the most general / useful for visualisation.

- The key questions for data visualisation are the limitations of a particular technology
  - Ability to create convoluted / concave structures
  - Colour reproduction
  - The finest structures / details that can be represented

Hardware

- ZCorp (http://www.zcorp.com/)

- Solved overhanging problem by using powder rather than liquid.

- Injet printer, prints coloured glue instead of ink onto a rising bed of powder rather than paper.

- 300 to 600dpi depending on model
  - misleading, geometry or colour?

- Model 450 - ~20x20x25cm build volume
  Model 650 - ~50x40x20cm build volume

- Minimum structural size 2-3mm

- Minimum detail size 0.5mm

Hardware

- Objet, http://www.stratasys.com.

- Company formed in 1990.

- Recent patent expiration is one reason for the current rapid increase in other suppliers.

- This has been a game changer
  - High resolution
  - Fine structural detail
  - Handles arbitrary overhanging structures

- Lays down one of N materials, photopolymer layers are cured by UV light.

- One layer may be a water soluble material for creating support layers.

- Latest model (2014) can do N materials (colours) from a colour palette. (N=10 at the moment).

Hardware

- Makerbot
  http://www.makerbot.com

- Fused Deposition Modelling.

- PLA plastic, single colour from limited palette.

- Replicator 2x can print dissolvable supports or 60 degrees without supports.

- Multiple colours and dissolving material can be time consuming.

- ~$3K

- Australian distributer: http://thinglab.com.au/

Hardware

- Mcor IRIS
  http://www.mcortechnologies.com

- Relatively recent player / technology.
  [See mine pit example]

- Prints and cuts paper, one sheet at a time.

- No volume component to cost, unused material (paper) cannot be reused.

- Costs are replacement blades, glue, ink and paper.

- Higher colour fidelity, essentially an ink jet printer.

- Issues removing paper from internal structures.

- A4 paper, maximum depth of 15cm (3 reams).

Hardware … plethora of others
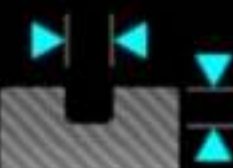
- Ultimaker
  https://www.ultimaker.com/
  - Comes as a DIY kit

- MarkForged
  - Prints in carbon fibre

- Airwolf 3D AW3D
  http://airwolf3d.com/

- Cartesio
  http://mauk.cc/
  One model has up to 4 extruders

- Clearly struggling to find sexy / techno
  names for new products.
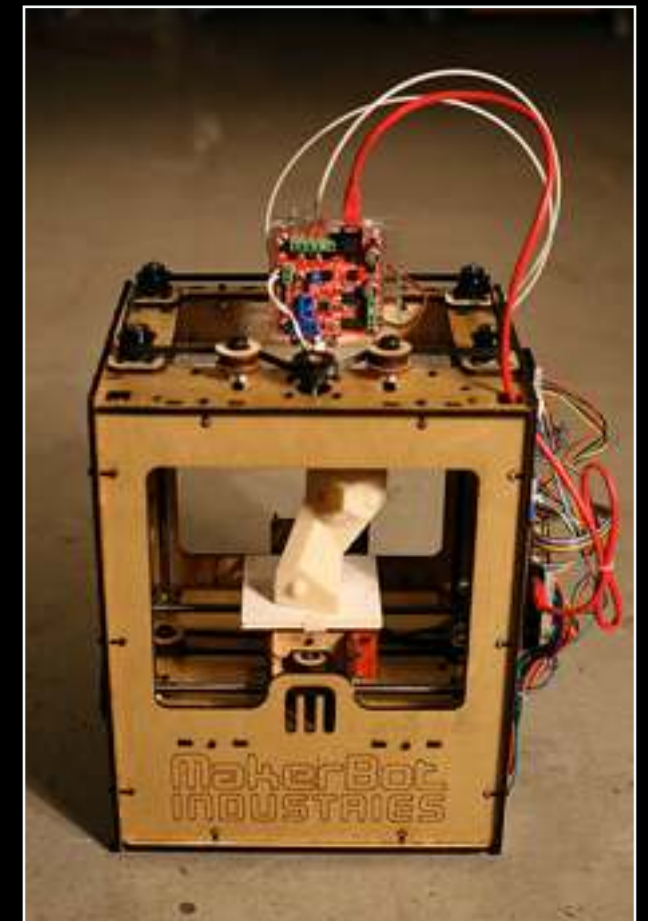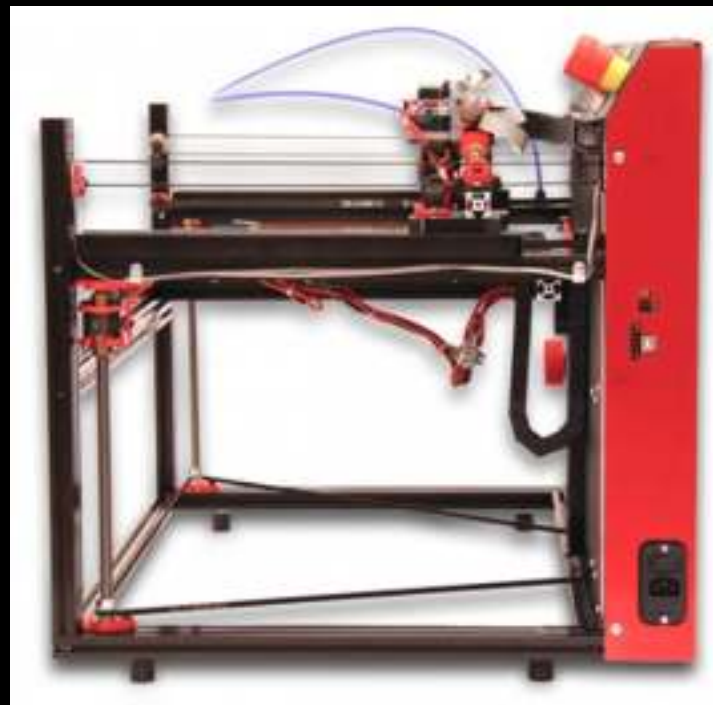
ZCorp and Objet

- Will focus on these two devices for the rest of the presentation.

- ZCorp
  - Colour support.
  - "sandstone"- like material (powder).
  - Limited in finest structures possible due to model fragility before cured.
  - Colour fidelity is limited.
  - Largest volume: 380 x 250 x 200.

- Objet
  - Monochrome (simple colour).
  - High structural strength, finer details, and a variety of materials.
  - Excellent support of convoluted objects {see 4 dimensional platonic solid].
  - Largest volume: 650 x 350 x 550.

- Online Shapeways bureau supports [see later] both including most of the material variants of the Objet printer.

Summary model limitations

		Zcorp (Colour SandStone)	Objet (White strongest)
Minimum supported wall thickness		2.0 mm	0.7 mm
Minimum unsupported wall thickness		3.0 mm	0.7 mm
Minimum supported wires		2.0 mm	0.8 mm
Minimum unsupported wires		3.0 mm	1.0 mm
Minimum embossed detail		0.4 mm	0.2 mm
Minimum engraved detail		0.4 mm	0.2 mm
Minimum escape holes		25 mm	4 mm
Minimum clearance between parts		0.9 mm	0.5 mm

Metal models

- There are some customised "wire extruders", very limited application.

- Usually built in one of two ways.

- Make a mold of the object and inject liquid metal.
  - Similar model parameter limitations as ZCorp printing.

- Build the model with glue onto a steel powder, later infusion process replaces glue with bronze.
  - More restrictive model parameters than ZCorp since intermediate stage is "soft".

Suppliers: Shapeways

- Shapeways
  http://www.shapeways.com

- Offers a storefront, wide range of materials.

- Comparatively cost effective.

- VERY stringent model checking. Models that can readily be built are often rejected.

- Textured models uploaded by creating a zip file of all components required.

- Will reprint for free if defects occur during manufacture.
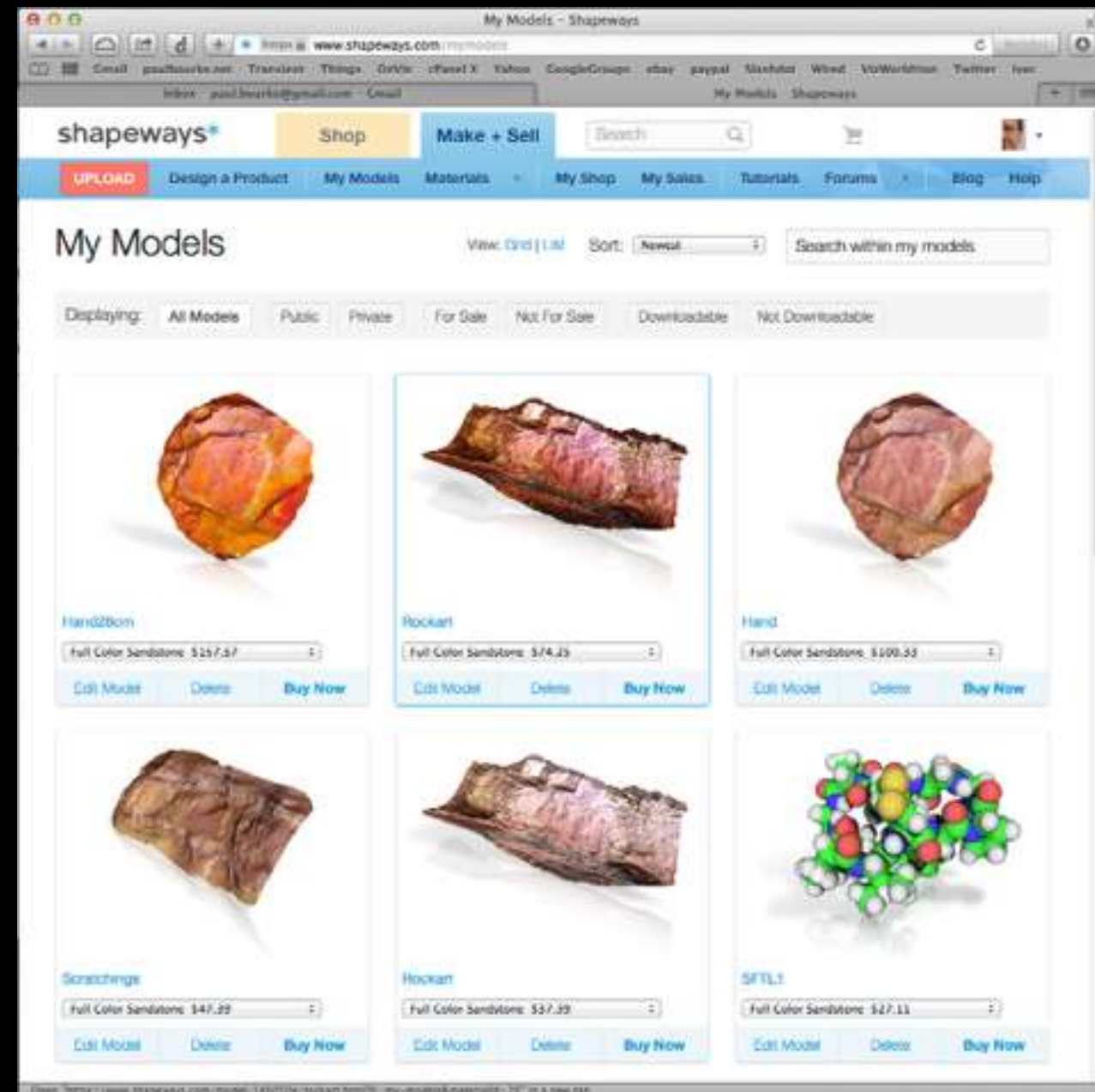
Suppliers: Other

- Increasing number of bureau services. Simply search for a combination of keywords "3D printing", "rapid prototyping".

- Some offer a combination of scanning and printing.

- These are not recommendations
  - ARRK: http://www.arrk.com.au/
  - Solidconcepts: http://www.solid-concepts.com.au
  - Rapid Models: http://www.rapidmodels.com.au
  - RapidPro: http://www.rapidpro.com.au
  - Thingiverse: http://www.thingiverse.com

- Personally use a Hong Kong company: http://www.rapman.hk
  Very cost effective for large models.

- Photoshop CC (Create Cloud), interface between their software and Shapeways.

Costs

- Almost always a function of the volume of deposited material.

- Exceptions are devices like the paper printer where it is more related to surface area, how fast the blade is worn.

- Also some coatings like gold on bronze are (obviously) a surface area cost.

- ZCorp colour: ~ $0.80 / cm^3

- ObJet strong plastic: ~ $1.50 / cm^3
  Some other plastics are as high as ~ $2.50 / cm^3

- Cost benefits to making models hollow.
  [See plane filling example].

- Of course there needs to be a way for the polymer or powder to escape so that it can be reused.

Buy or use a bureau service?

- My advice is to use a bureau unless you have high volume and dedicated staff.

- While there are low cost 3D printers, the higher quality ones (ObJet) can be expensive. Usual technology story, twice the quality for an order of magnitude higher cost.

- Advantages of buying
  - Immediate models
  - Can print models that might not pass automated tests (Questionable)

- Disadvantages of buying
  - Old out of date hardware in 3-4 years
  - Operator time and equipment maintenance

- Advantages of a bureau
  - Generally more expert operators
  - Can provide a range of technologies
  - Quality control, reprint errors or corrupt models
  - Lower costs due in part to filling printing volume

- Disadvantages of a bureau
  - Delivery delay

File formats

- **STL**: **ST**ereo**L**ithography

- The original format designed for the "old style" engineering rapid prototyping.

- The lowest denominator, supported by all printers.

- Plain text (human readable) as well as more file size efficient binary version.

- Cannot convey colour information, just defines triangular faces and optionally normals.

- Easy to generate from code and easy to read in order to convert into another format.

- Supported by a wide range of 3D software packages.

```
solid
    :
    :
    facet normal 0.0 0.0 1.0
    outer loop
        vertex  1.0  1.0  0.0
        vertex -1.0  1.0  0.0
        vertex  0.0 -1.0  0.0
    endloop
    endfacet
    :
    :
endsolid
```

File formats

- **STL**: **ST**ereo**L**ithography

- I have a small C library of useful functions for creating geometry in STL format.

  FILE *STLOpen(char *)
  void STLClose(FILE *)
  void STLQuad(FILE *,XYZ *,int)
  void STLTri(FILE *,XYZ *)
  void STLSphere(FILE *,XYZ,double ,int , int)
  void STLCyl(FILE *,XYZ,XYZ,XYZ,XYZ,int,double,int)
  void STLBox(FILE *,XYZ,XYZ)

File formats

- **VRML**: **V**irtual **R**eality **M**odelling **L**anguage (.wrl)

- X3D: An ISO standard royalty free XML-based file format, managed by the Web3D consortium.

- A family of related formats that have evolved over the last 15 years.

- Supports colour (vertex and facet) and textured models.

- The format of choice for most colour printing.

```
<?xml version="1.0" encoding="UTF-8"?>
<X3D profile="Interchange" version="3.2">
<Scene>
  <Shape>
    <IndexedFaceSet coordIndex="0 1 2">
      <Coordinate point="0 0 0 1 0 0 0.5 1 0"/>
    </IndexedFaceSet>
  </Shape>
</Scene>
</X3D>
```

File formats

- **VRML**: **V**irtual **R**eality **M**odelling **L**anguage

- Also have a small library of useful functions for creating .wrl files.

  void WRLHeader(FILE *,char *,double)
  void WRLLine(FILE *,XYZ *,int,COLOUR)
  void WRLSphere(FILE *,XYZ,double,COLOUR)
  void WRLCone(FILE *,XYZ,XYZ,double,double,int,COLOUR,int)
  void WRLFace(FILE *,XYZ *,int,COLOUR)

File formats

- **OBJ**: **OBJ**ect format originally from WaveFront.

- Human readable format for mesh data consisting of a vertex list, vertex normals, texture coordinates, and face definitions in terms of vertex/normals/texture indices.

- Can support colour and textures.

- Widely supported.

- A model generally consists of three files:
  - obj file describing geometry
  - mtl (material file) linking geometry to colour and texture files
  - one or more texture images as jpg or png.

- My choice for textured models.

- Reasonably easy to create and parse. No binary version.

```
mtllib panel.mtl
v 2.063131 -0.353800 5.319475
v 2.414187 0.018440 5.322199
v 2.406885 0.018508 5.320719
  :
  :
vt 0.259852 0.158293
vt 0.259871 0.307778
vt 0.259877 0.079314
  :
  :
  :
vn 1.770880 -2.076491 -5.336680
vn -5.164361 -2.113251 -0.315065
vn 0.661940 -5.829563 2.180070
  :
  :
usemtl material_0
f 20/48/20 11/501/11 29/47/21
f 70/42/70 71/143/71 59/13/55
f 58/30/58 70/142/70 59/13/55
  :
  :
```

File formats

- **Collada**: **Colla**borative **d**esign **a**ctivity (.dae)

- ISO standard managed by Kronos standards committee.

- Increasingly supported by 3D applications.

- Not particularly convenient for data export from ones own software.
  There are a number of APIs / libraries to assist with this.

- Relatively complicated given the simple requirements of 3D printers.

File formats

- Hints for packaging models for Shapeways.

- Except for STL the other formats do not encapsulate the textures in a single file.

- Create a zip file with model and textures.

- For OBJ the archive would typically include:
    OBJ text file + .mtl file + image textures
  .mtl files are text, human readable, define colours or form the link between parts in the OBJ file and texture images.

- All bureaus and 3D printing software will impose limits on the size of model then can handle. For Shapeways the limits are 64MB (zip file not unzipped) and 1 million polygons.

Geometry: creating lines / curves

- Lines and curves are infinitely thin, cannot be physically realised.

- Need to be represented as meshes, collections of facets (triangular bounded plane sections).

- Approach is to turn lines into cylinders and seal them with spheres or endcaps.

- Can result in a very large number of triangular faces.

Model for connectivity in the visual cortex.

Spherical join

Endcap

Spherical endcap
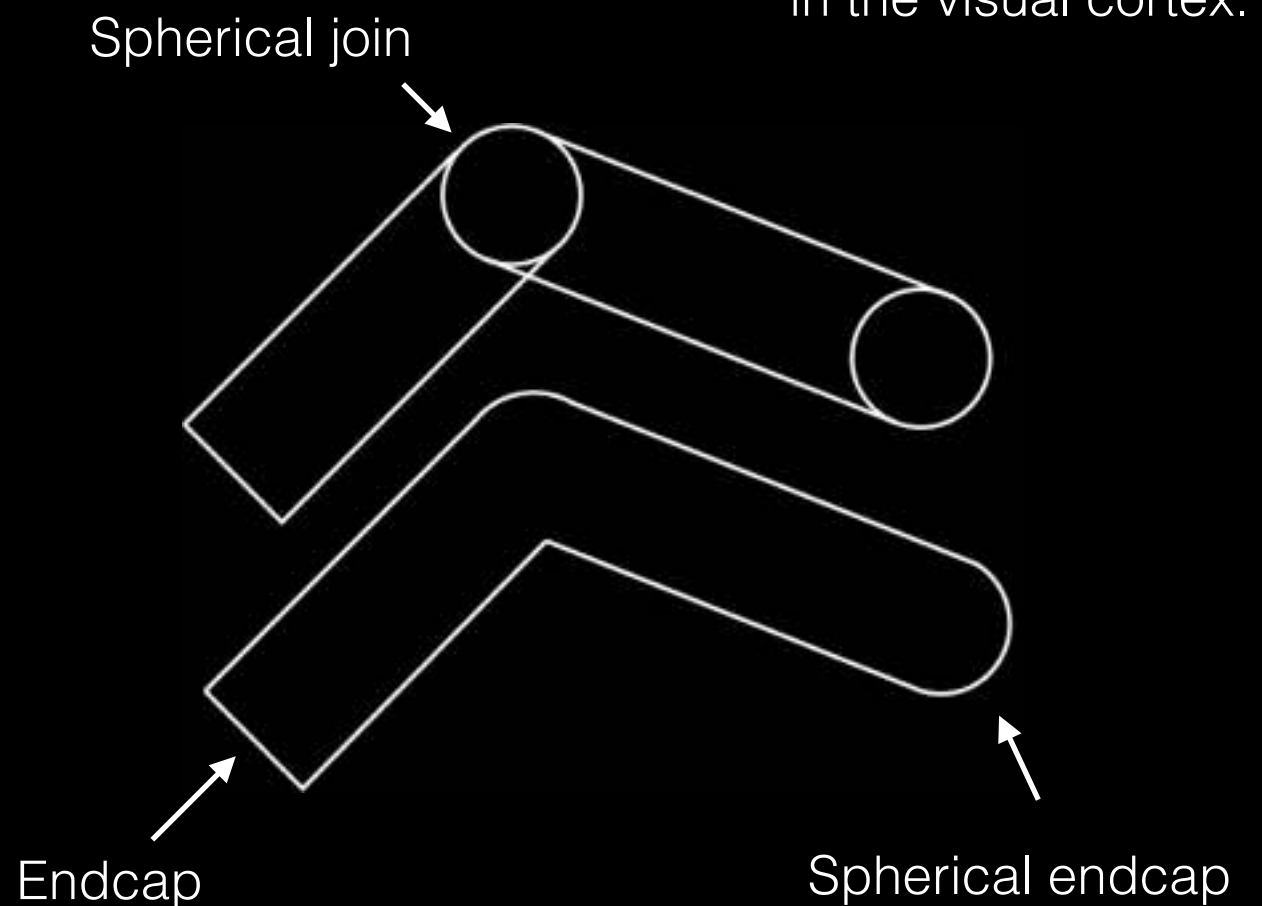
Geometry: creating lines / curves

- Lines and curves formed as a large stack of spheres. Inefficient but easy.

- Important to get the face normals pointing in the right direction, outwards.
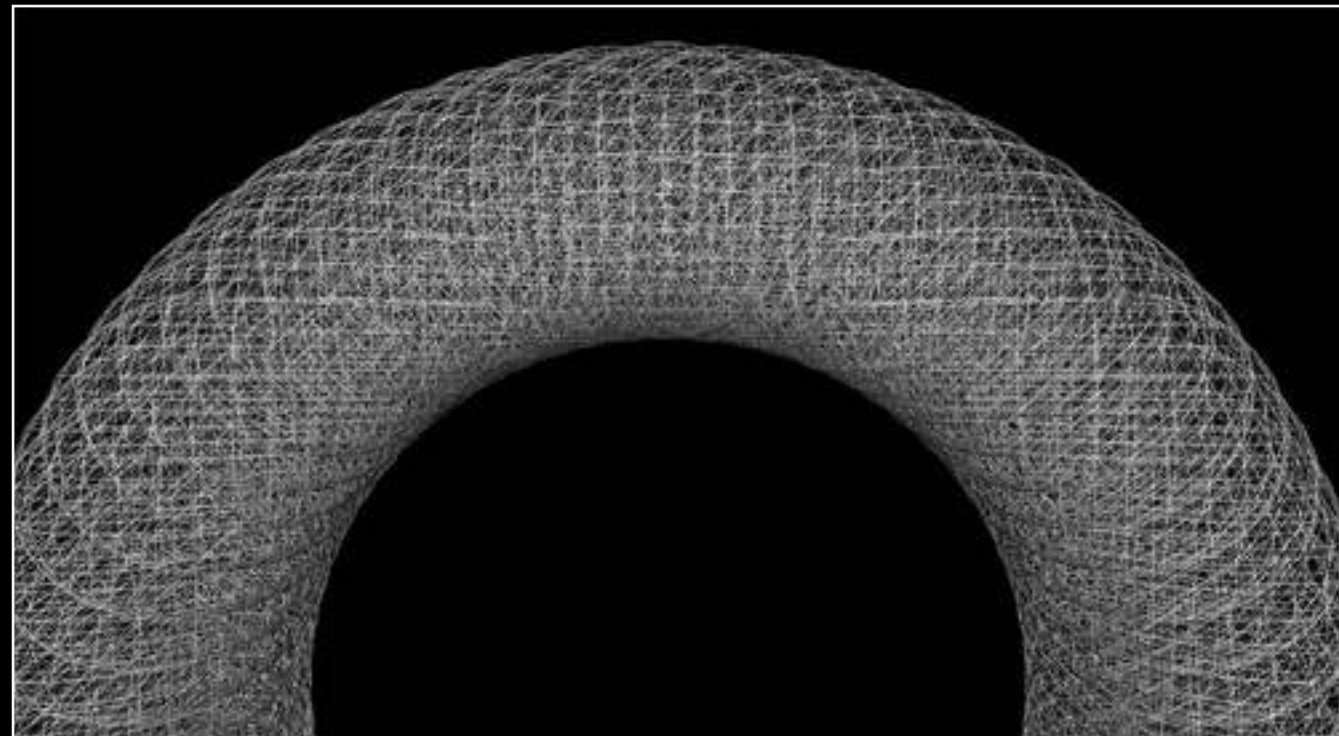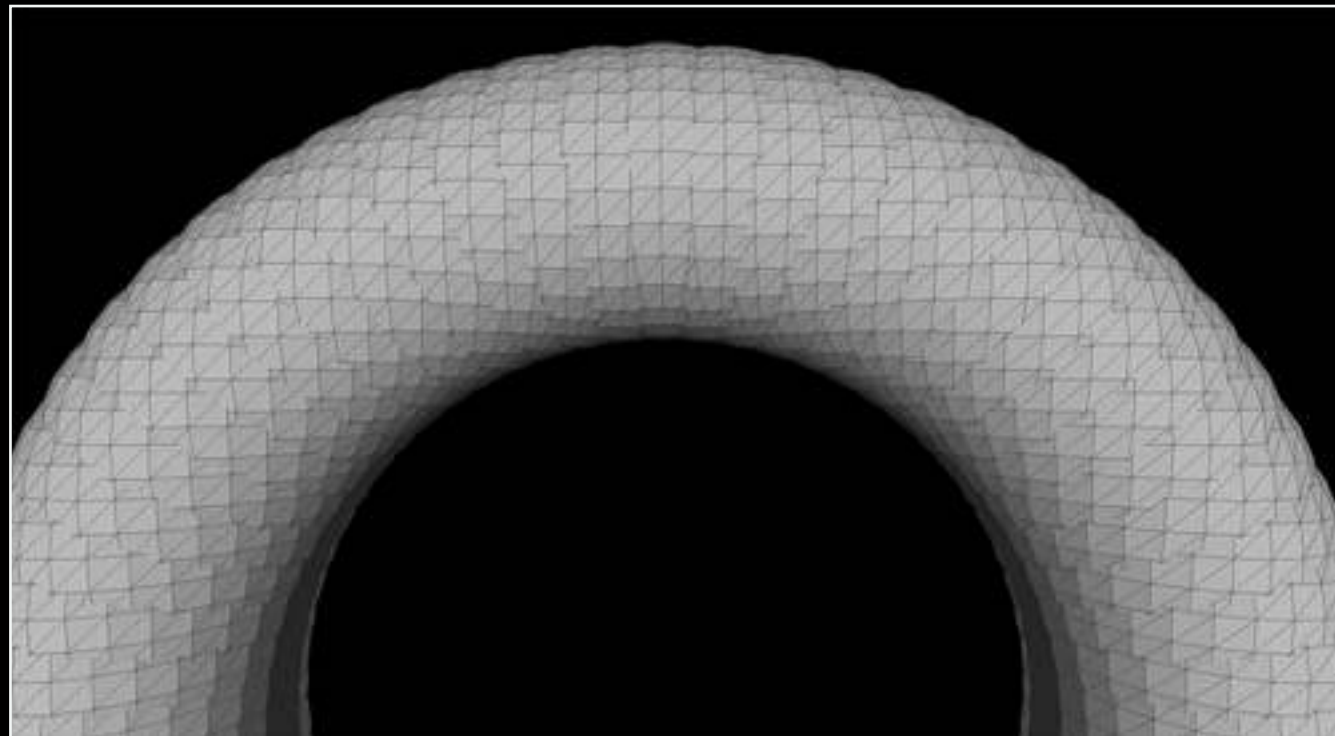
Geometry: lines and curves

- More efficient to create spheres at vertices and cylinders between spheres.

- Interior structures inefficient but otherwise does not affect the model.
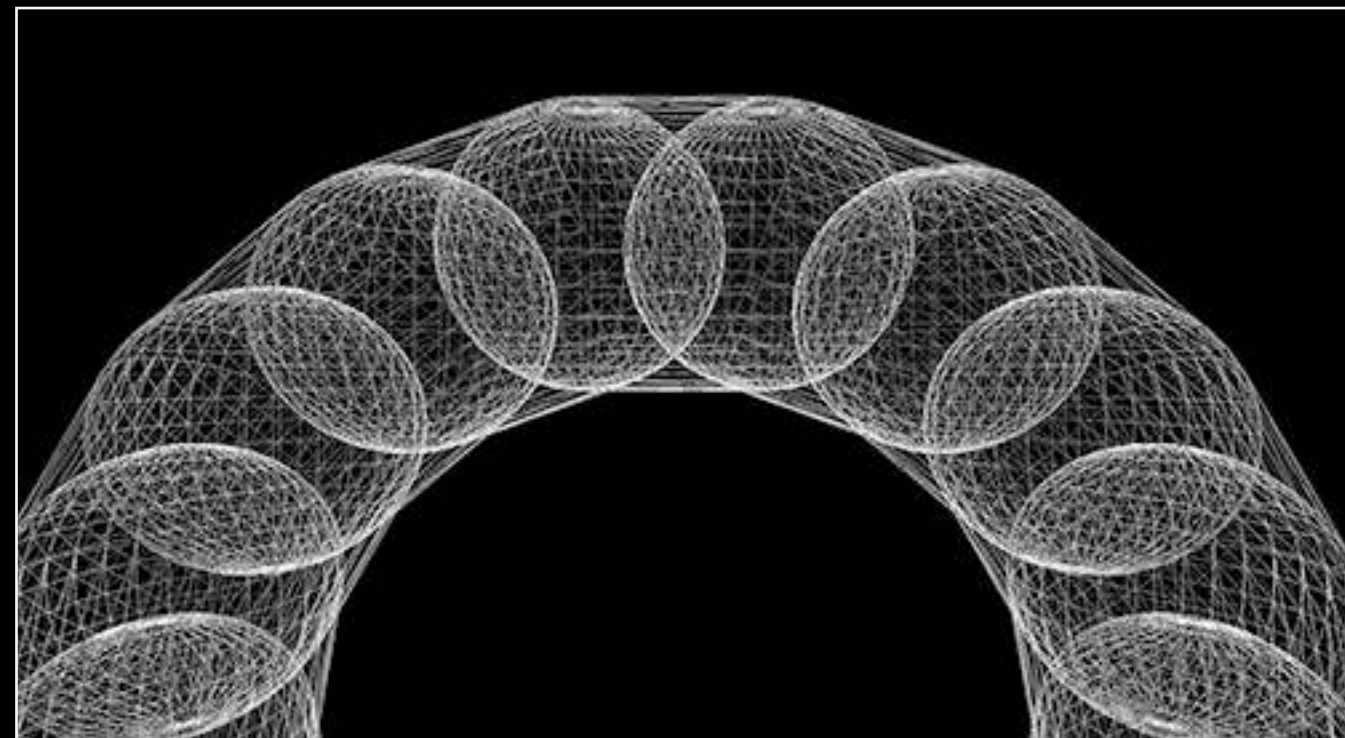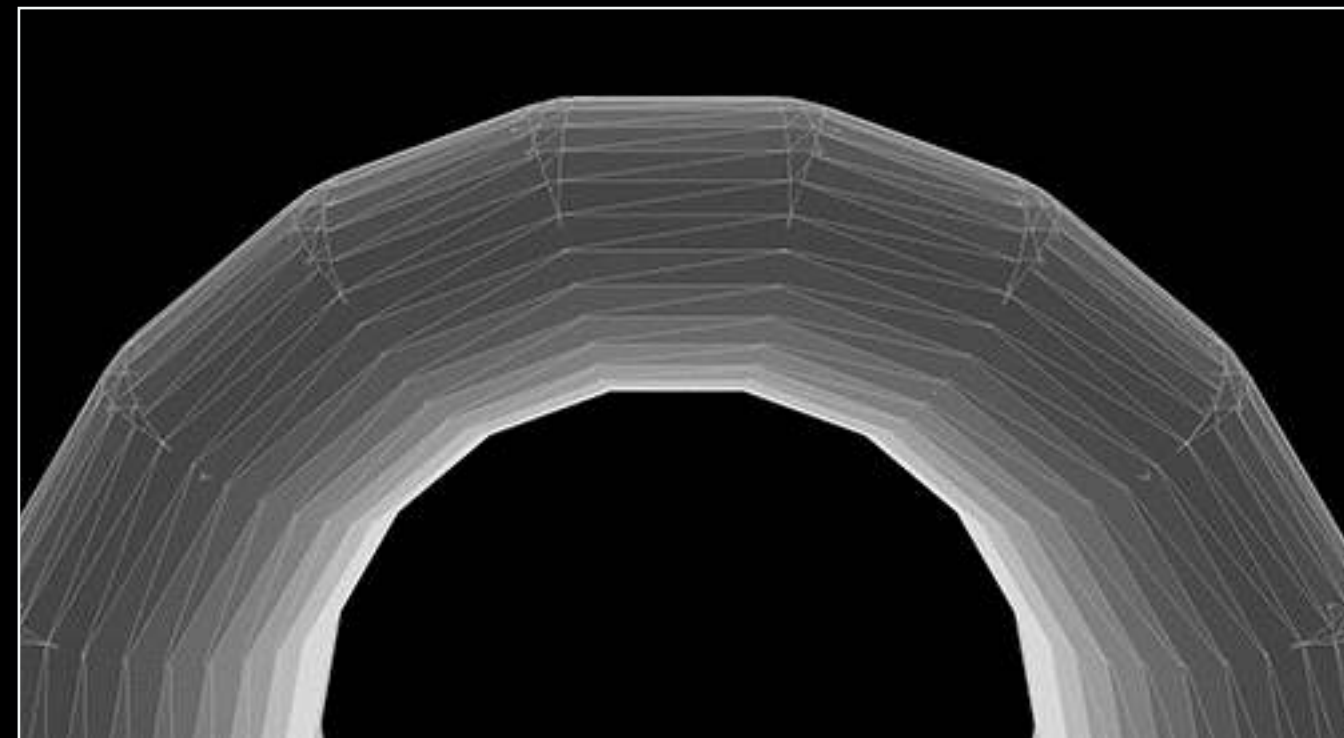
Geometry: manifold

- Formally manifold means the surface is locally Euclidean.

  Practically for 3D printing ….

- Objects must be "watertight", will hold water.
  [Merge close vertices, see MeshLab later]

- Any edge may not be shared by more than two faces.
  (Mathematically known as 2-manifold)

- No coincident faces.

- Consistent outward pointing normals.

Geometry: thickening surfaces

- A surface / mesh in 3D computer graphics, like an idealised point or line, is infinitely thin. As such is unrealisable physically.

- A triangle/quad/mesh then needs to be "thickened" to some minimal thickness in order to be printed.

- One might imagine solution is to extrude the triangles making up the mesh along their normals. This simple approach can have issues for areas of high curvature.
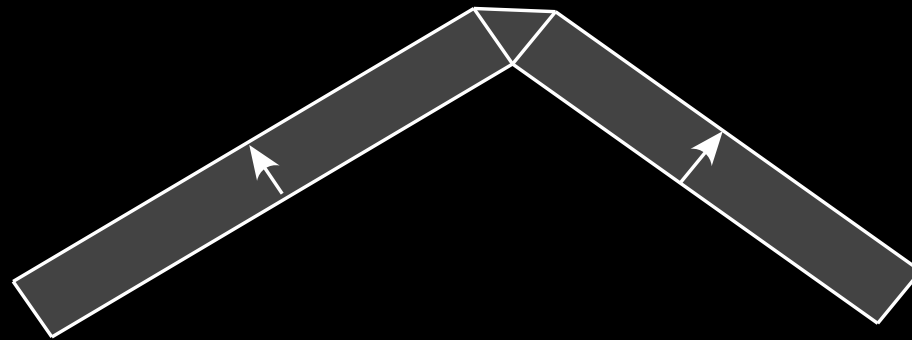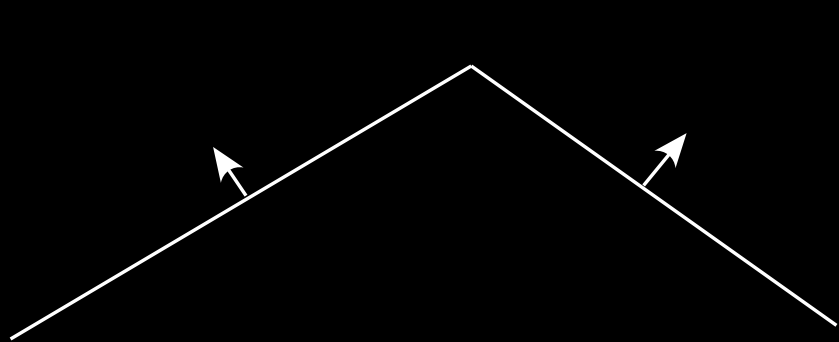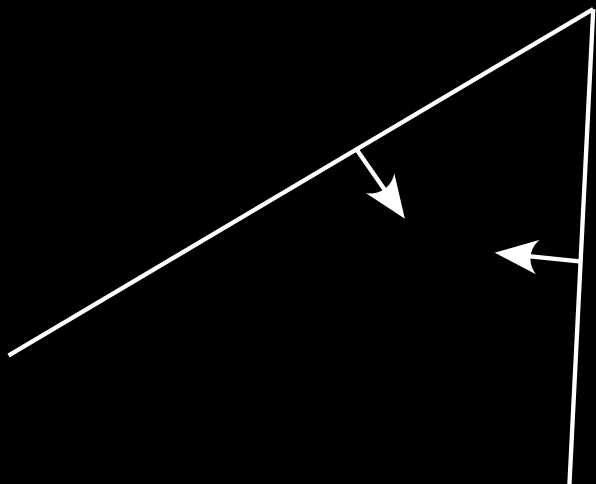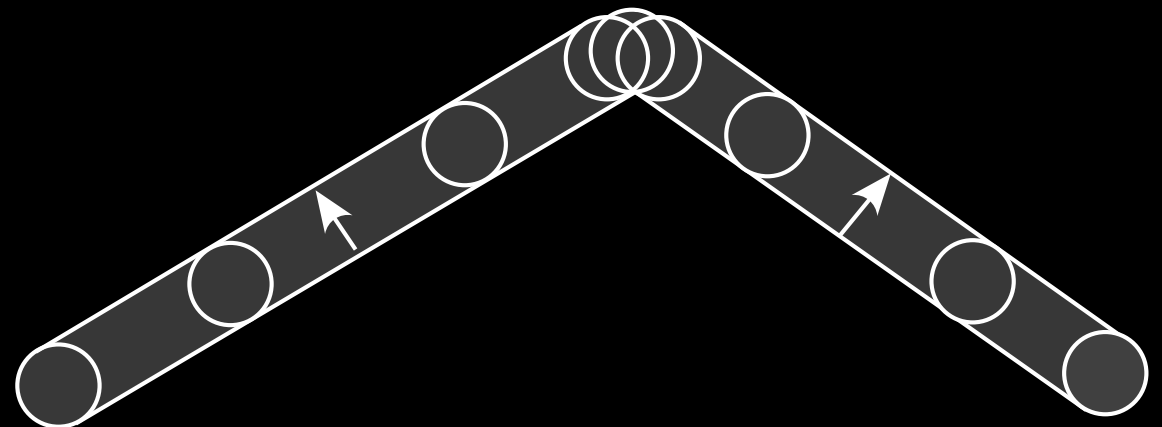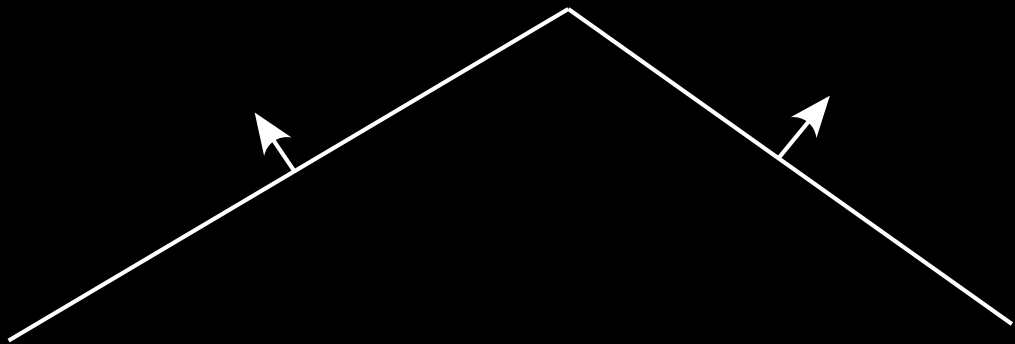
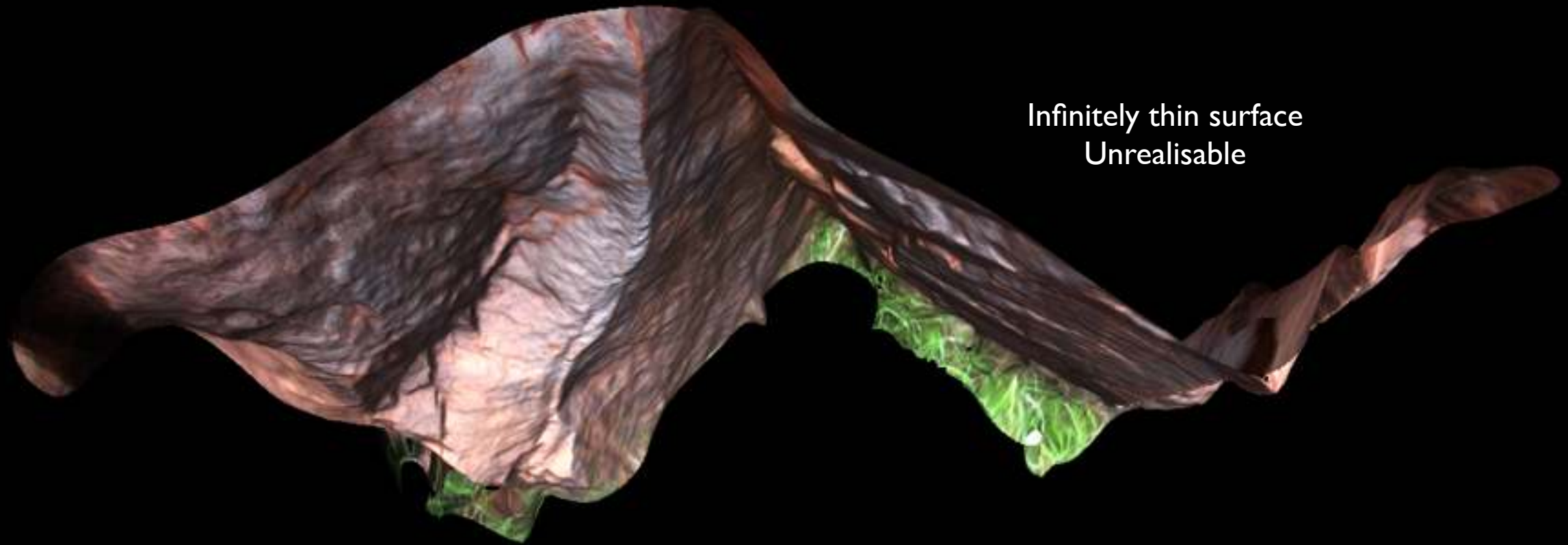Thin joints arise at
regions of high curvature
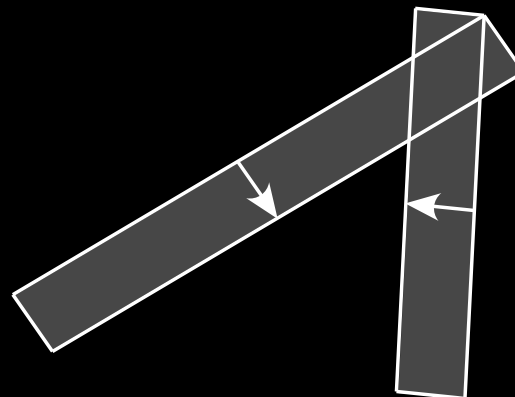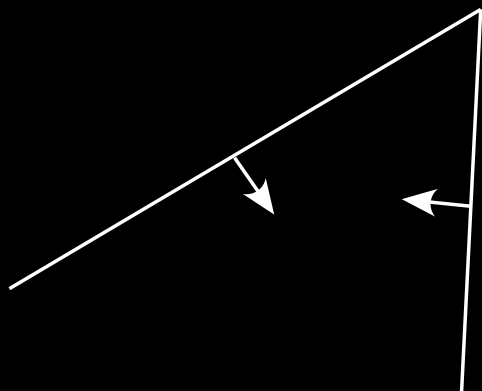
Get "poke-through" with
sharp concave interiors

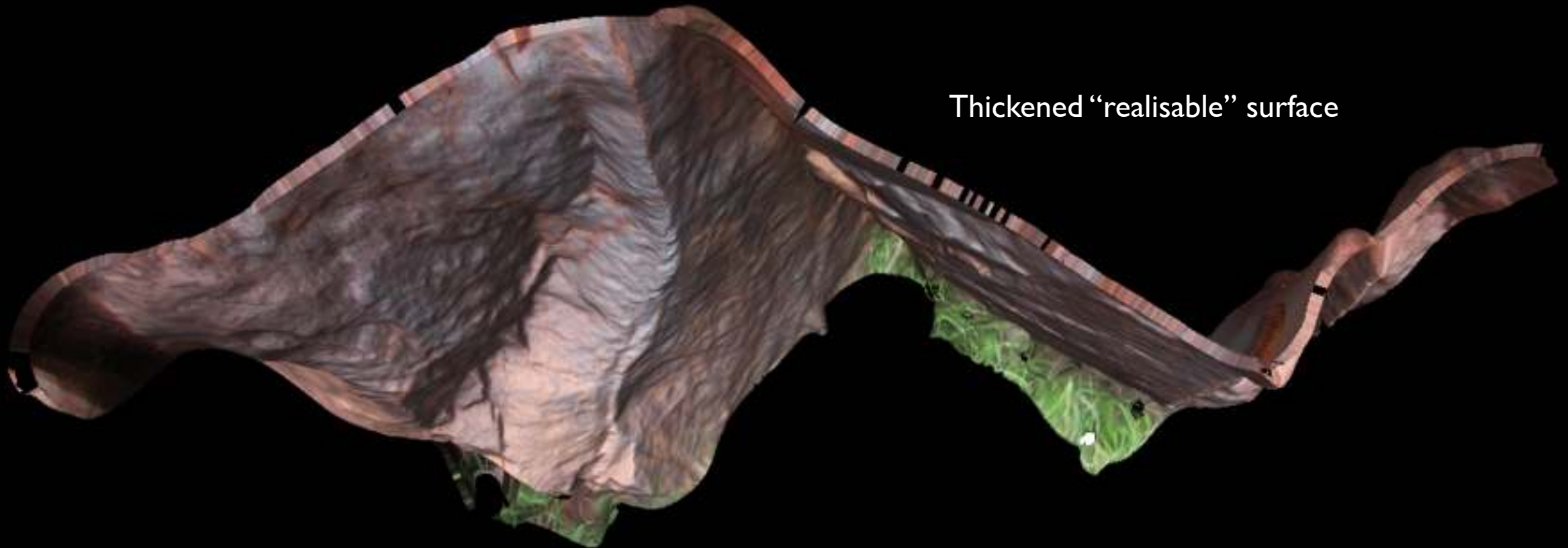# Geometry: thickening surfaces

- Solution is called "rolling ball" thickening.

- Imagine a ball rolling across the surface, form an external mesh along the ball path.

- Implemented in Blender as a modifier called "solidify".
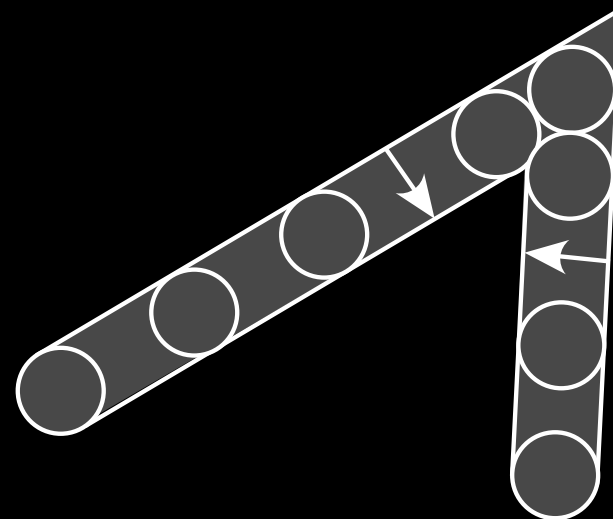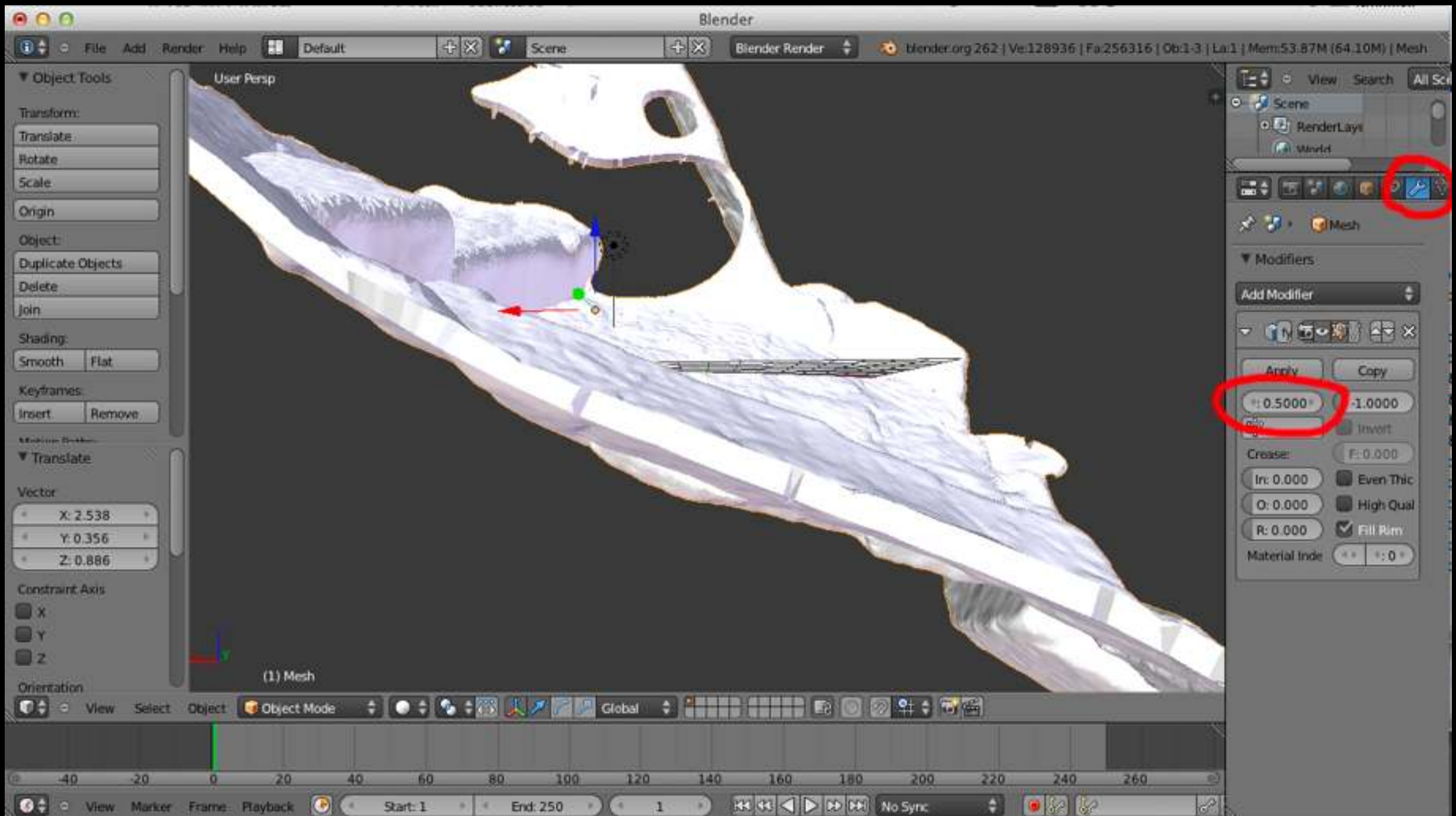
Geometry: thickening surfaces

Infinitely thin surface
Unrealisable

Thickened "realisable" surface

Geometry: thickening surfaces

- "Solidify" modifier in Blender.

- Modifiers are elegant since they don't permanently affect the geometry, can change later.

Software: Meshlab

- General coloured / textured mesh editing tool with a wide range of algorithms.

- OK for cleaning unwanted pieces. Not suitable for vertex level editing, see Blender.

- Good for mesh simplification and smoothing, see mesh polygon count limits.

- Use for converting and exporting to suitable file formats.

- Other useful Meshlab functions
  - merge close vertices
  - removing unused vertices or polygons
  - removing duplicate vertices or polygons
  - closing holes
  - "quadratic edge collapse decimation" to simplify meshes

Software: Meshlab
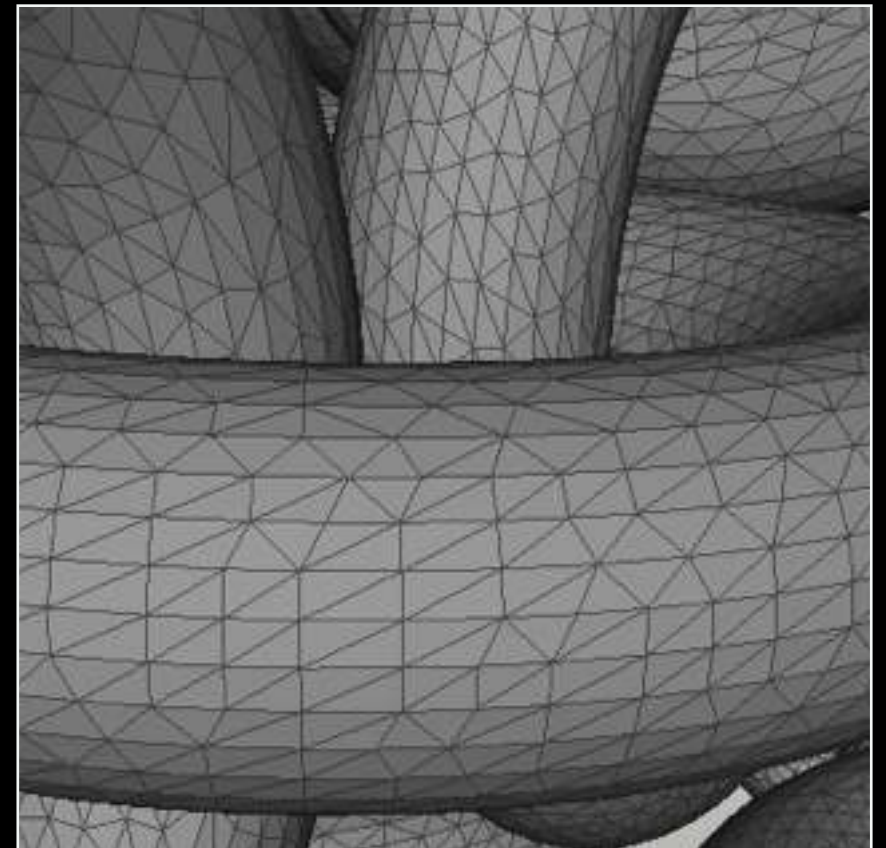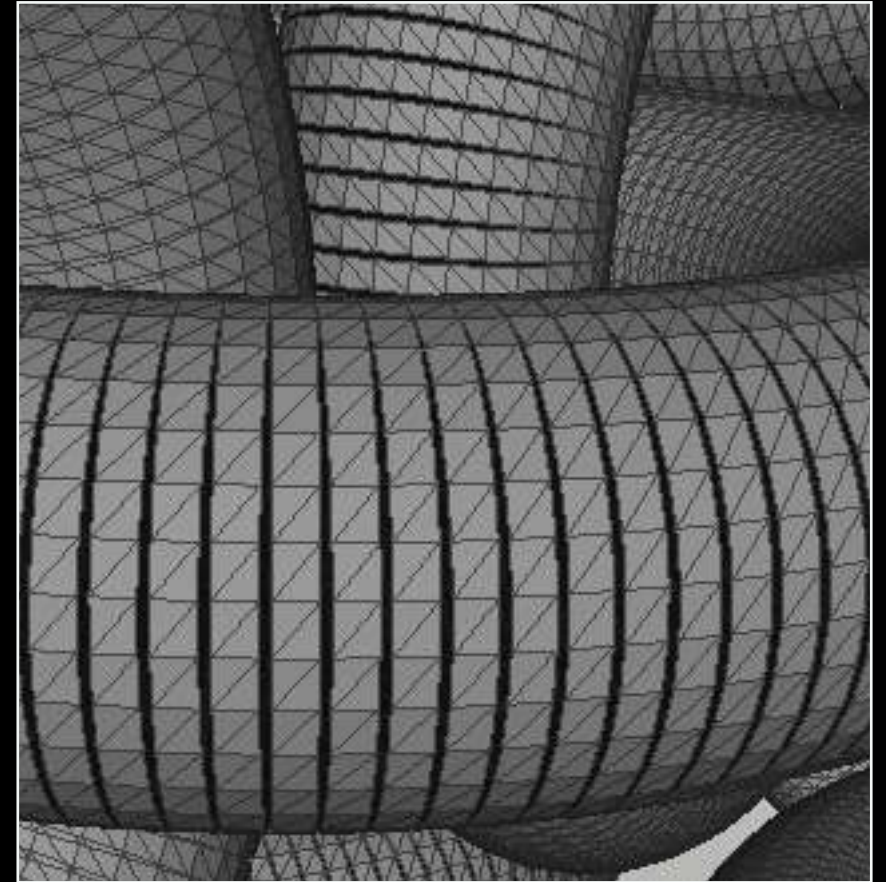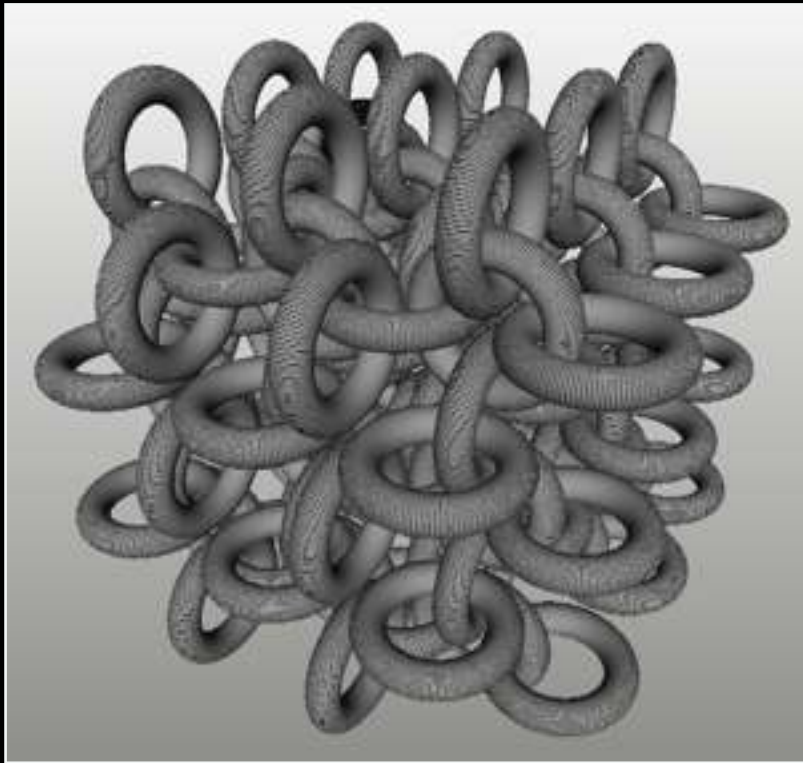
- An example. Merge close vertices and mesh simplification.

- Problems with model are:
  - the gaps between the cylinders.
  - too many triangles.

- Original model: 194MB and 1.2 million triangles.

- Final model: 25MB binary STL and 1/2 million triangles.

Software: Netfabb

- NetfabbTool designed specifically for rapid prototyping.
  Especially targeted to identifying problems with models.
  Can actually be used to drive (some) 3D printing machines.

- Commercial, available for Mac, Windows, and limited Linux support.
  Professional version ~$2000, private version ~$400.

- Personally find it less useful especially since it seems to have poor support for textured models.

- Tools for hollowing out models and thus making some models more economic.
  Could quickly recoup the cost for this feature alone.

Software: Blender

- Open source and cross platform full featured 3D modelling / animation / rendering software.

- Already mentioned use for thickening surfaces.

- Ideal tool for vertex level editing.
  Although this can be time consuming.

- Some learning curve involved but not too bad for a limited set of relevant operations.
  Good online tutorials.

Examples - Questions - Discussion