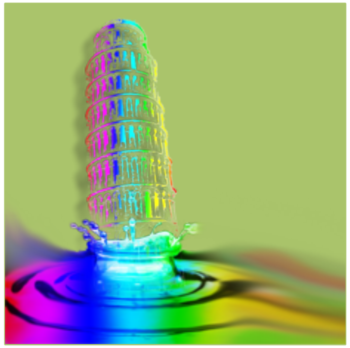
Softwares for 3D printing

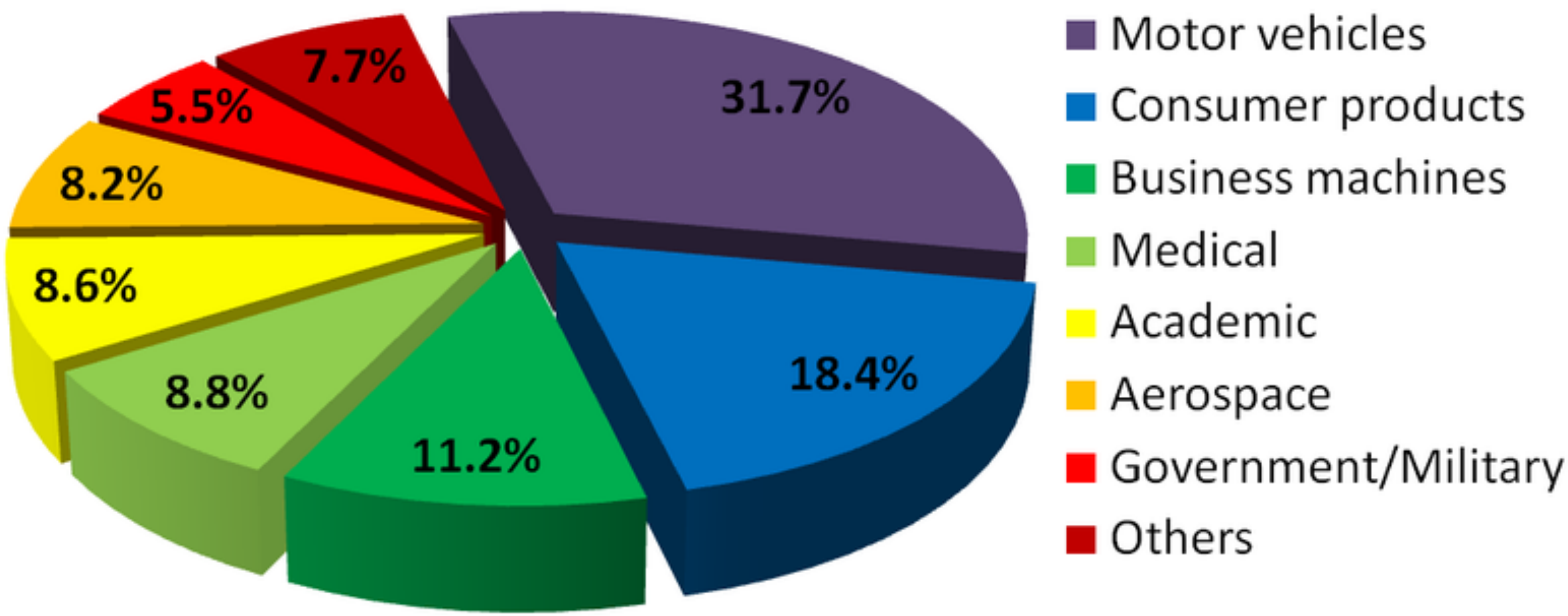


carmelo.demaria@centropiaggio.unipi.it

3D world

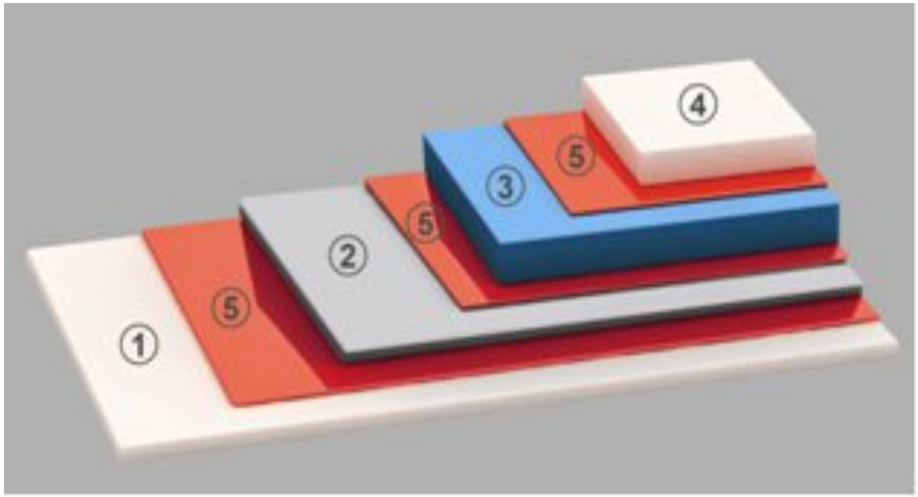
A picture says than 1000 words ...
... a model tells the whole story

Rapid Prototyping by Industry Sectors:



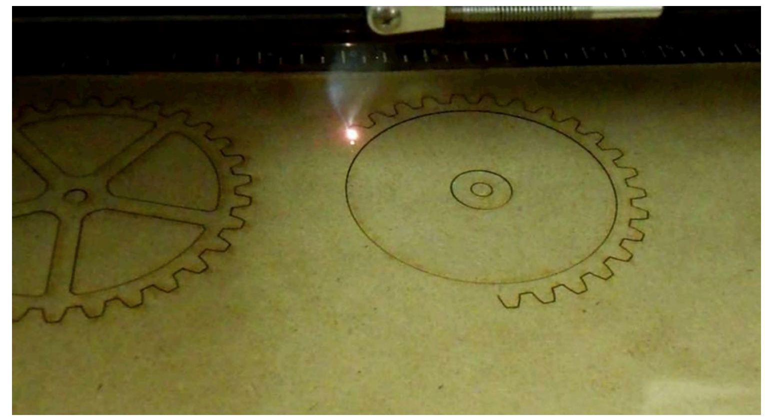
Tecnologie 3D

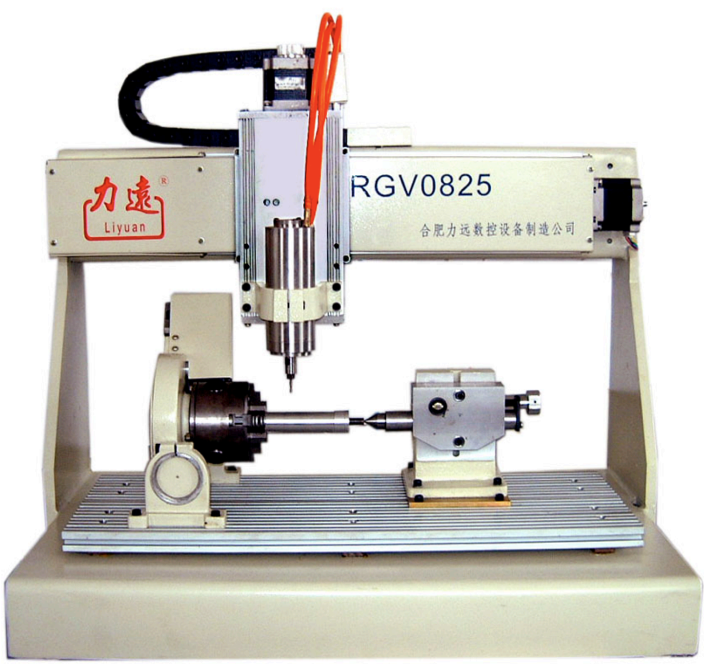
- Sottrattive
- Additive



Subtractive technologies

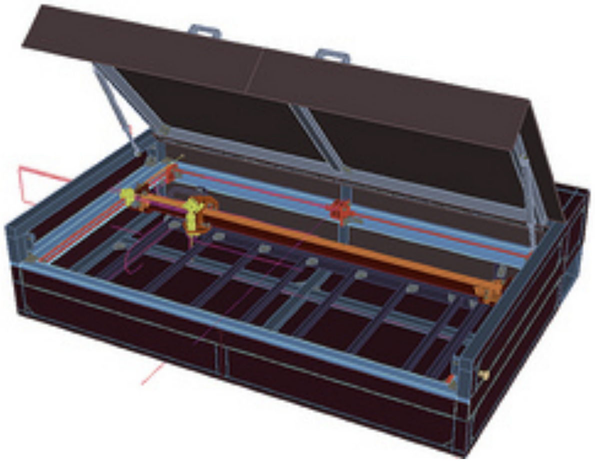
- Laser cutter
- CNC milling machines





Open Subtractive technologies

- Laser cutter
- CNC milling machines

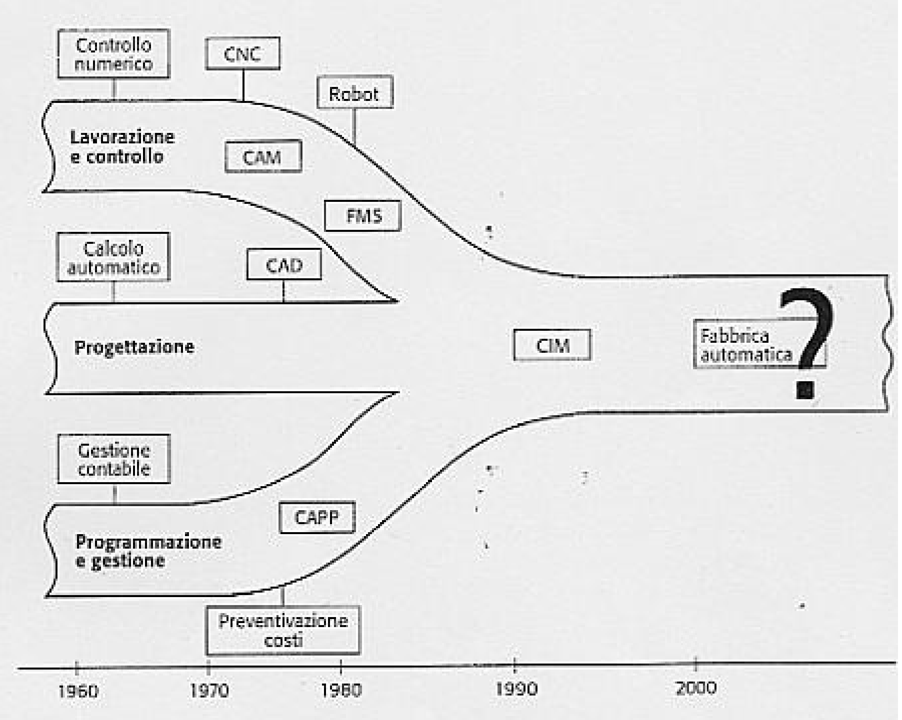


www.buildyourcnc.com

http://labs.nortd.com/lasersaur/

Tecnologie CAx

- CAD – Computer Aided Design
- CAE – Computer Aided Engineering
- CAM – Computer Aided Manufacturing
- CAPP – Computer Aided Process Planning
- CIM – Computer Integrated Manufacturing



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3D printing

- 3D printing (or Additive Manufacturing) is a process of making a three-dimensional solid object of virtually any shape from a digital model.
- 3D printing is achieved using an additive process, where successive layers of material are laid down in different shapes.

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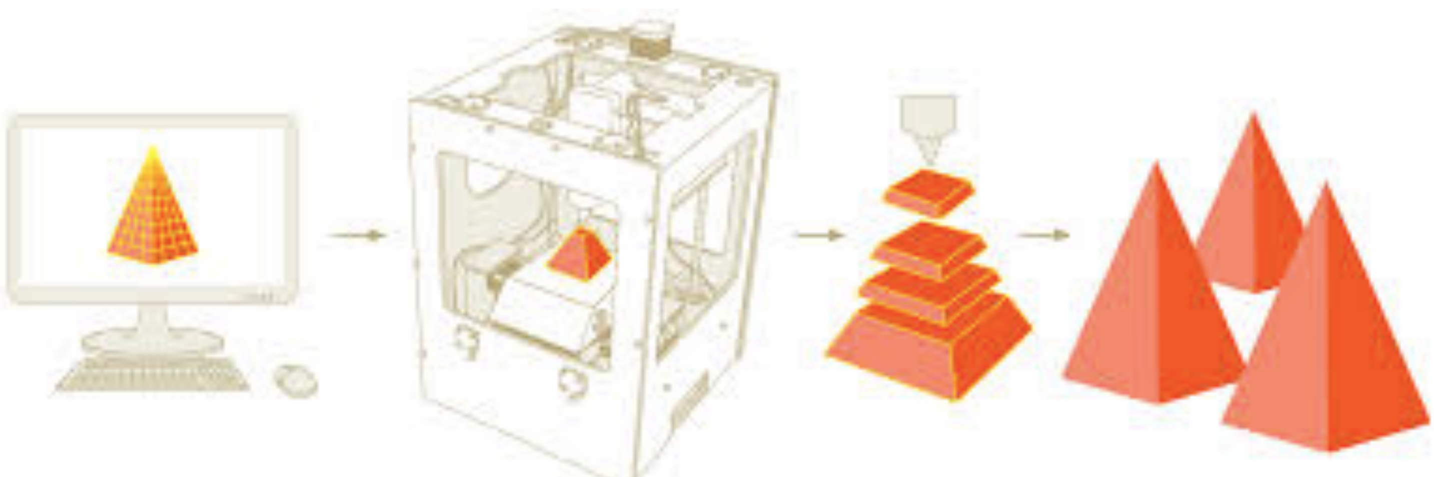

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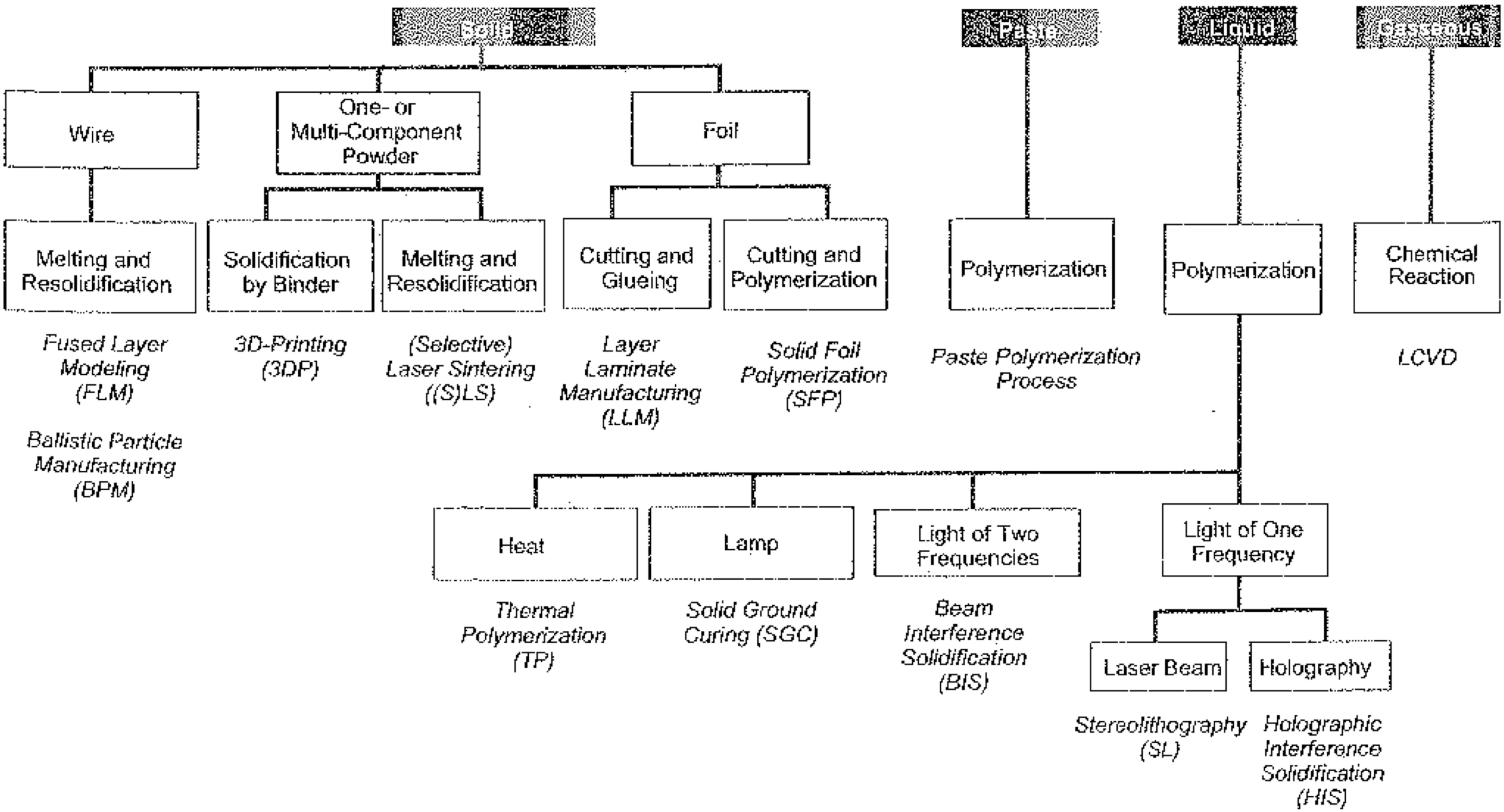
Una possibile classificazione



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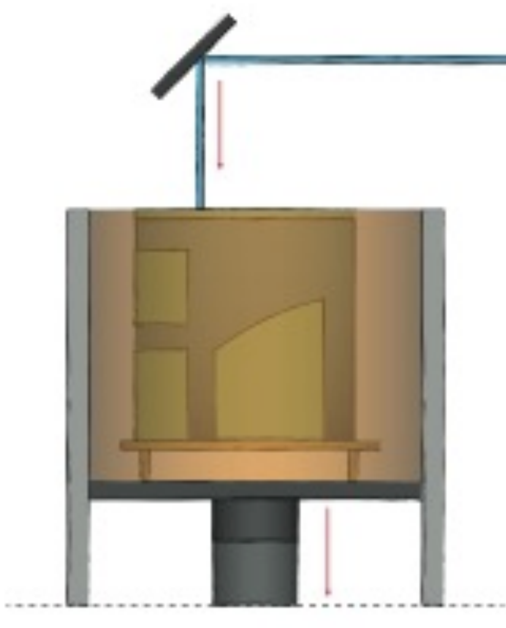
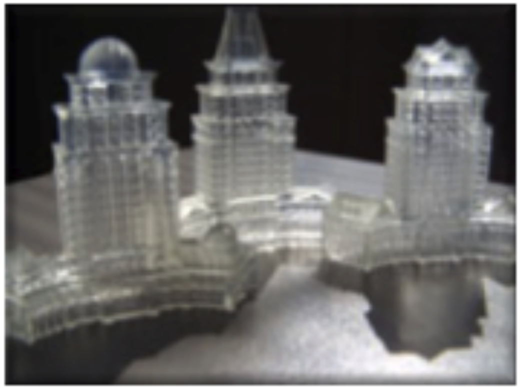
Available technologies

- Solidification of liquid materials
  - Photo-polymerization process





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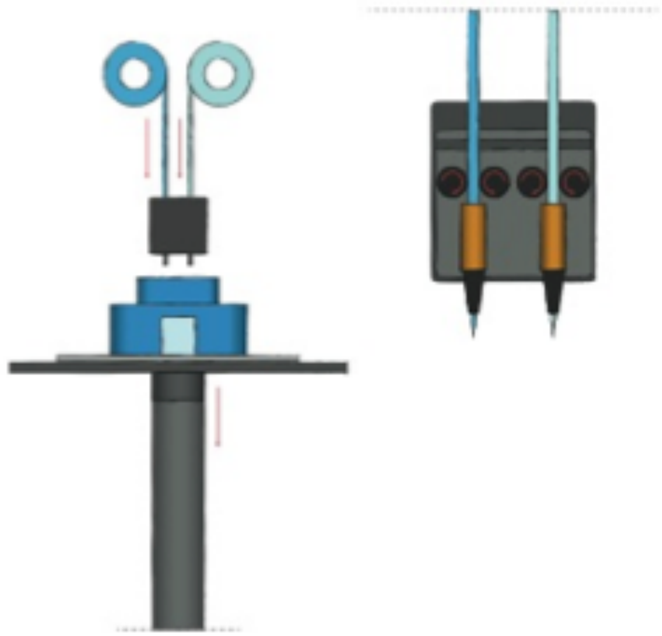
Available technologies

- Generation from the solid phase:
  - incipiently or completely melted solid materials, powder, or powder mixtures:
    - Extrusion (FDM),
    - Ballistic and
    - Sintering processes

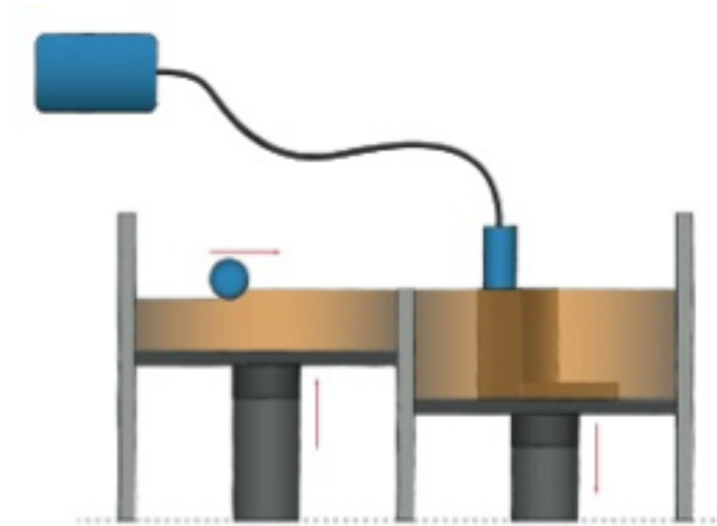


Available technologies

- Generation from the solid phase:
  - incipiently or completely melted solid materials, powder, or powder mixtures:
    - Extrusion (FDM),
    - Ballistic and
    - Sintering processes

Available technologies

- Generation from the solid phase:
  - Conglutination of granules or powders by additional binders
    - 3D inkjet printer



RAPID PROTOTYPING

Rapid Prototyping Process Flow

- Solid Modelling
- Tesselation/Generation of STL file
- Support Generation
- "Slicing" of the Model
- Model Physical Buildup
- Cleanup and Post Curing
- Surface Finishing

Rapid Prototyping Process Flow

File

CAD FILE → STL FILE → GCODE

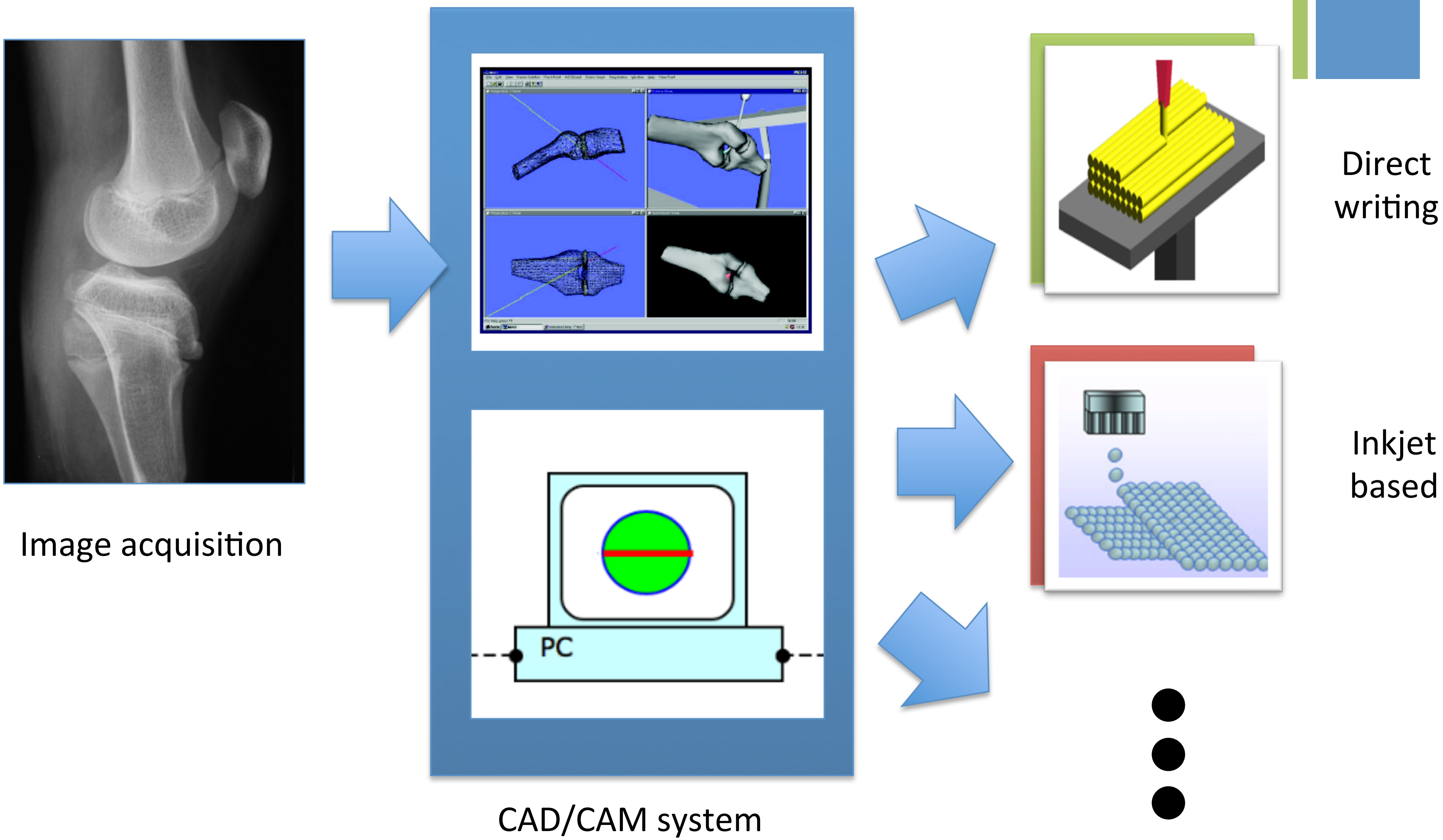
Description

3D object → Triangle and vertex → Toolpath

Software

FreeCAD → FreeCAD (MeshLab) → Slic3r → Printrun to 3DP

Rapid Prototyping Process Flow



Sorgenti dati

- Dati di tipo volumetrico
  - Modello CAD
  - Provenienti da strumentazione
    - CT
    - RM

Modello CAD

Dimensions of CAD Elements	Elements	Type of CAD Model
0D	Point	Corner Model
1D	Line	Edge Model
2D	Surface	Surface Model
3D	Solid/Volume	Solid or Volume Model

Esempio

DA IMMAGINI MEDICHE A STL

Segmentazione

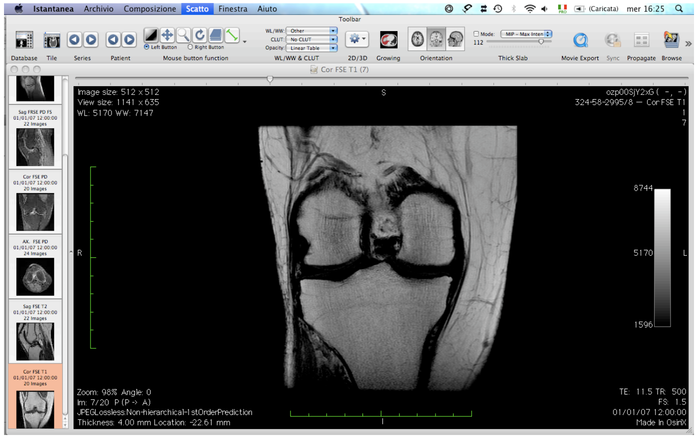
- Segmentation subdivides an image into its constituent regiorns or objects.
- The level to whhc the subdivision is carried out depends on the problem being solved

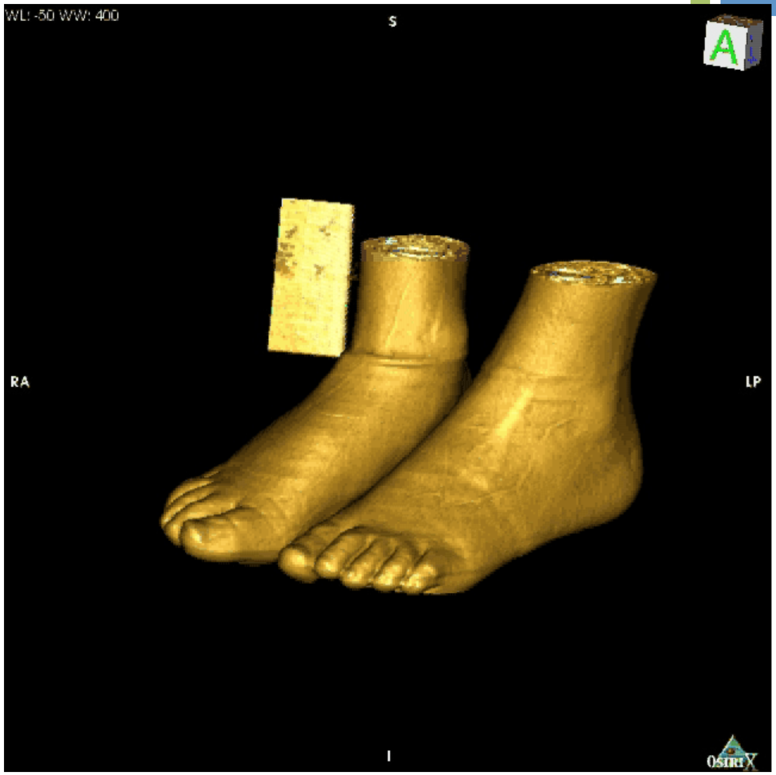
Software per l'analisi delle bioimmagini

- OsiriX (www.osirix-viewer.com)
- 3DSlicer (www.slicer.org)
- ImageJ (rsb.info.nih.gov/ij)
- MIPAV (mipav.cit.nih.gov)
- itk-SNAP (www.itksnap.org)

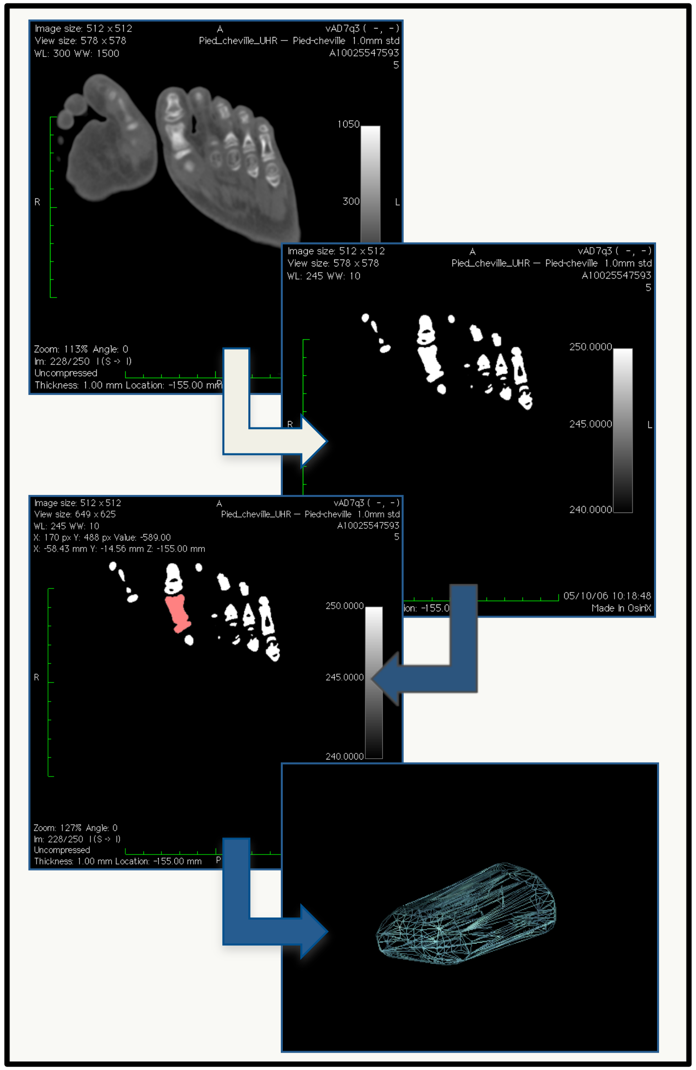
+ Image Analysis: OxiriX imaging software

- Advanced open-source DICOM PACS workstation
- Image processing
- Better communication with surgeons

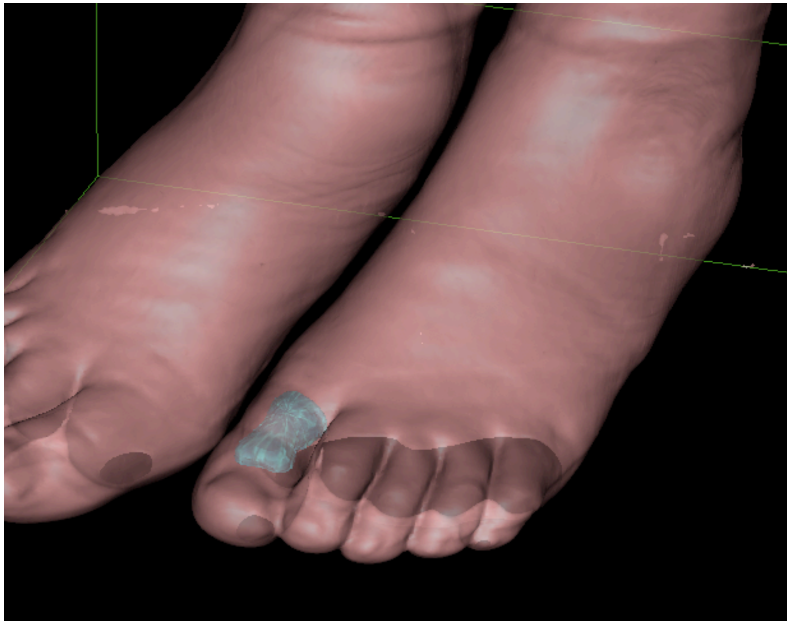




Geometry extraction

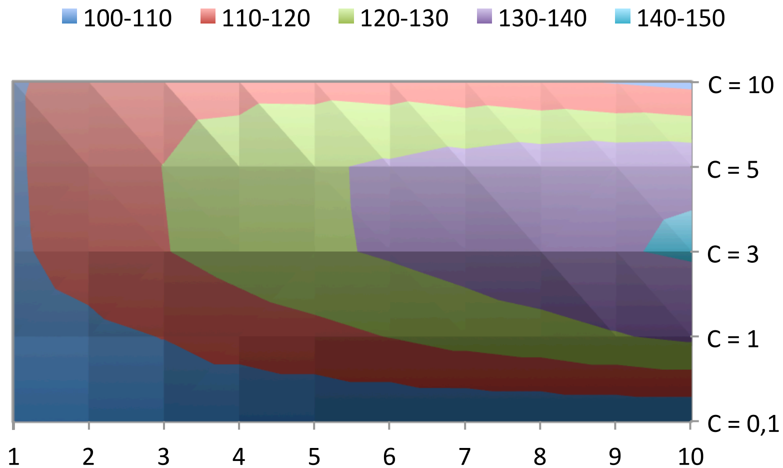


- From original CT DICOM image to final volume
- Semi-automatic procedure
- Positive results in 95% of cases

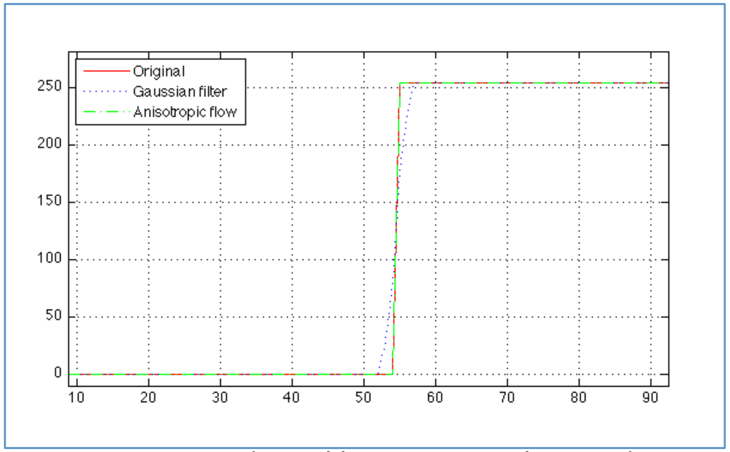


Osirix Plugins: edge preserving smoothing

- Analogy between "heat diffusion" and image blurring
- Preserve edges varying "heat conductivity" in accord to image region:
  - Gradient anisotropic diffusion,
  - Curvature anisotropic diffusion,
  - Curvature flow
- Filters performance assessment

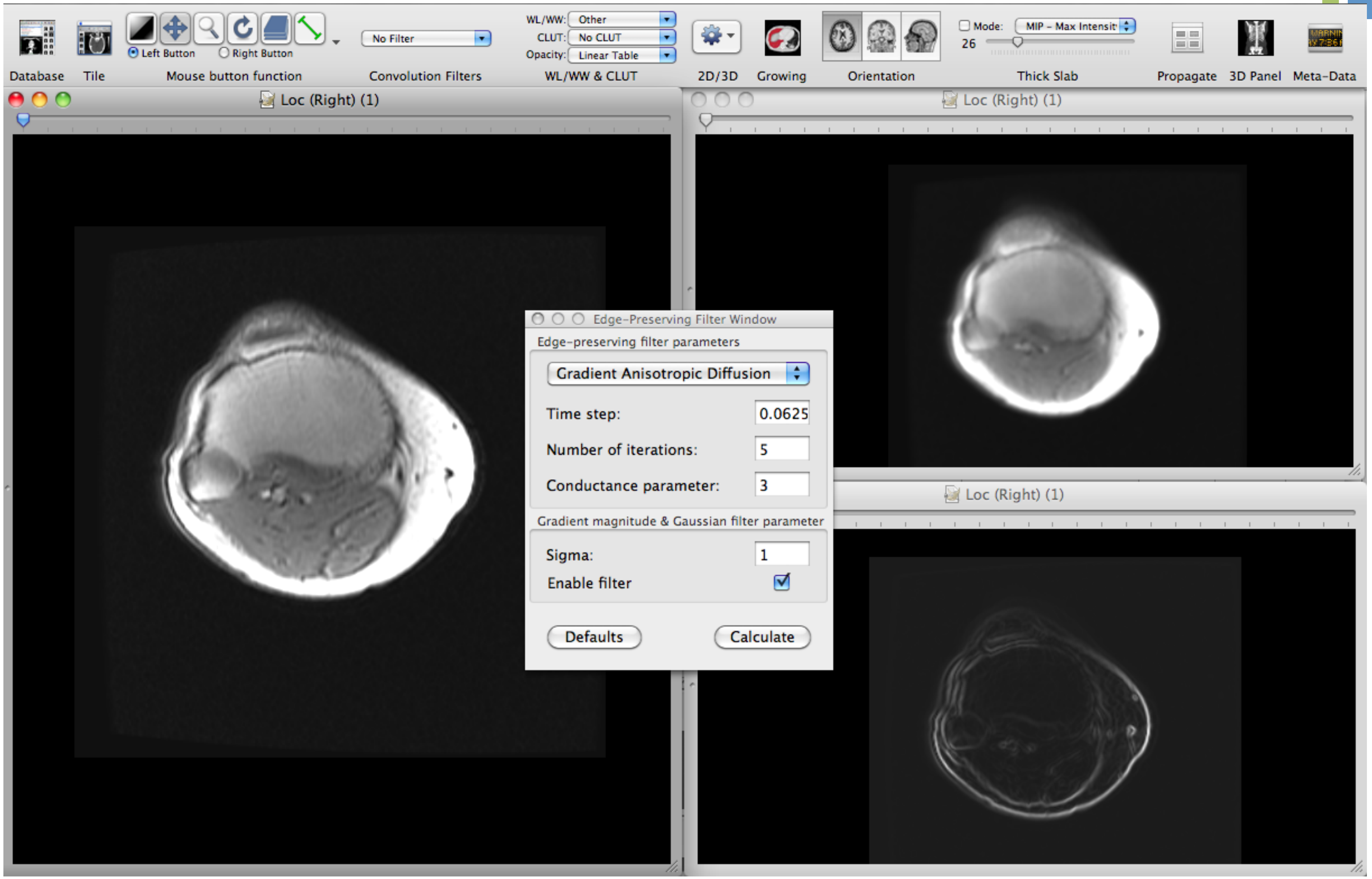


Gradient anisotropic diffusion



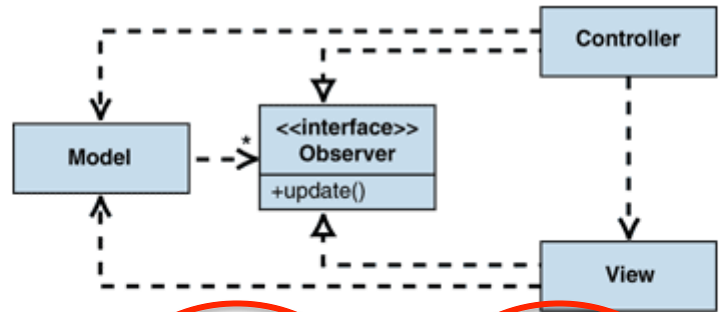
P Perona and J Malik. Pattern Analysis and Machine Intelligence, IEEE Transactions on, 12(7):629–639, 1990

Osirix Plugins: edge preserving smoothing

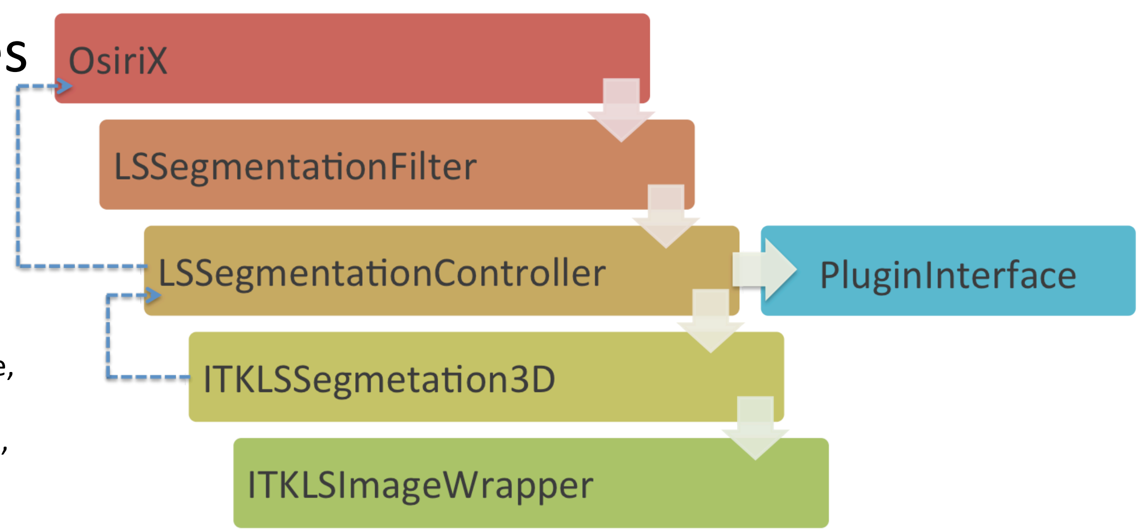


Osirix Plugins: Level-Set segmentation

- Two algorithm
  - Shape detection
  - Geodesic Active Contours
- Evolution based on
  - Propagation
  - Curvature
  - Advection
- Programming principles

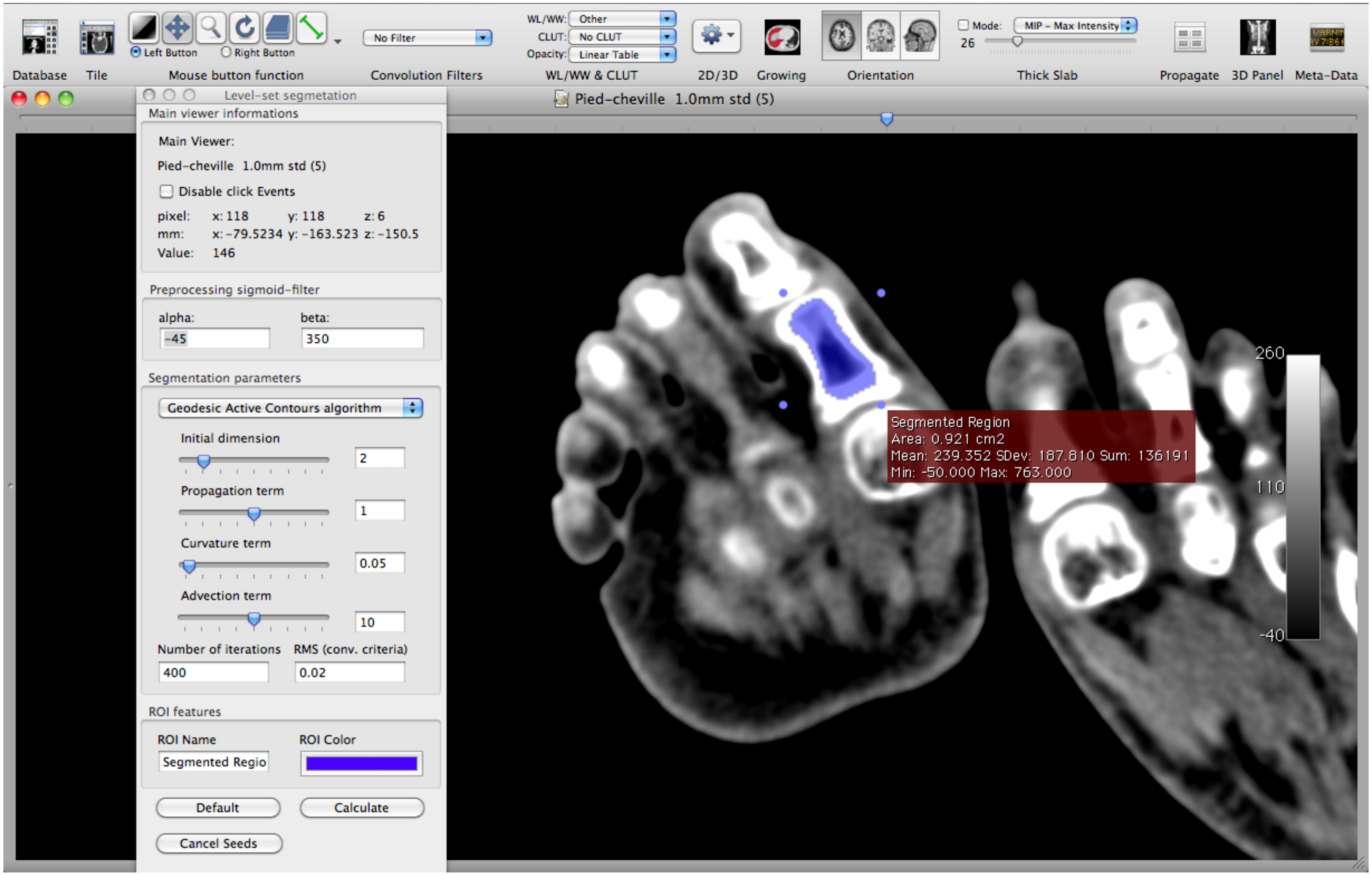


$$\frac{d}{dt}\psi = -\alpha \mathbf{A}(\mathbf{x}) \cdot \nabla \psi - \beta P(\mathbf{x}) \left| \nabla \psi \right| + \gamma Z(\mathbf{x}) \kappa \left| \nabla \psi \right|$$



R Malladi et al. Pattern Analysis and Machine Intelligence, IEEE Transactions on, 17(2):158 – 175, Feb 1995.
V Caselles et al. International Journal of Computer Vision, 22(1):61–79, 1997.

Osirix Plugins:
Level-Set segmentation



EXCHANGE FORMATS

Stereolithograpy Interface

- Stereolithograpy was first commercial Solid Freeform Manufacturing (SFM) process, released in 80’s by 3-D Systems
- 3-D Systems developed interface between CAD systems and their machine
- STL files (*.stl) allow CAD systems to interface with 3-D system machines
- Virtually all subsequent SFM processes can use this same format (SFM industry standard)
- Many CAD programs now can export the *.stl file for easy conversion from CAD to part

STL Files (*.stl)

- STL files were based on a program called Silverscreen CAD
- Silverscreen CAD represent boundary with all surfaces being approximated by polygons or groups of polygons
- *.stl files use triangles or groups of triangles to approximate surfaces
- Accuracy depends on the triangle sizes (Smaller facets produce a higher quality surface)
- Triangles assigned normal vectors for outward surface normal
- Parts are defined by representing all their bounding surfaces as faceted surfaces, using the triangular patches

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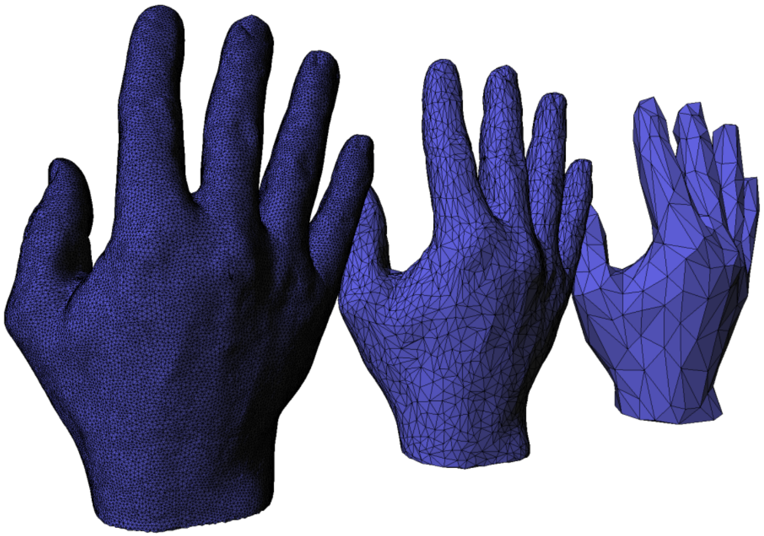
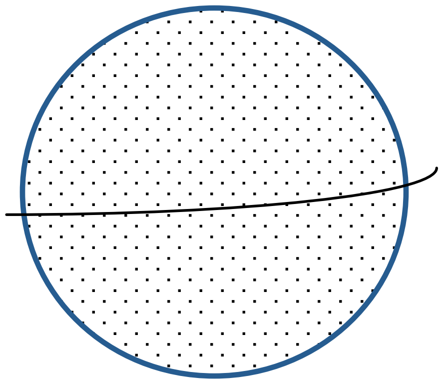
STL Files (*.stl)

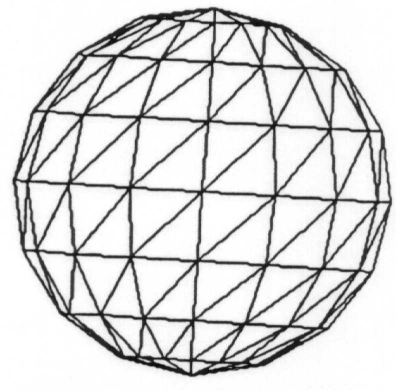
- STL files describe only the surface geometry of a three dimensional object without any representation of color, texture or other common CAD model attributes.
- An STL file describes a raw unstructured triangulated surface by the unit normal and vertices (ordered by the right-hand rule) of the triangles using a three-dimensional Cartesian coordinate system.

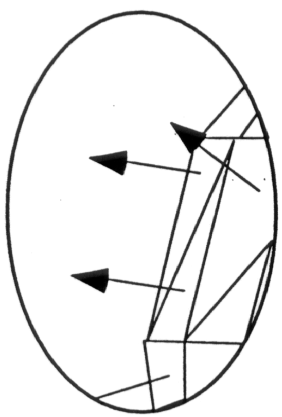


Example of *.stl Representation



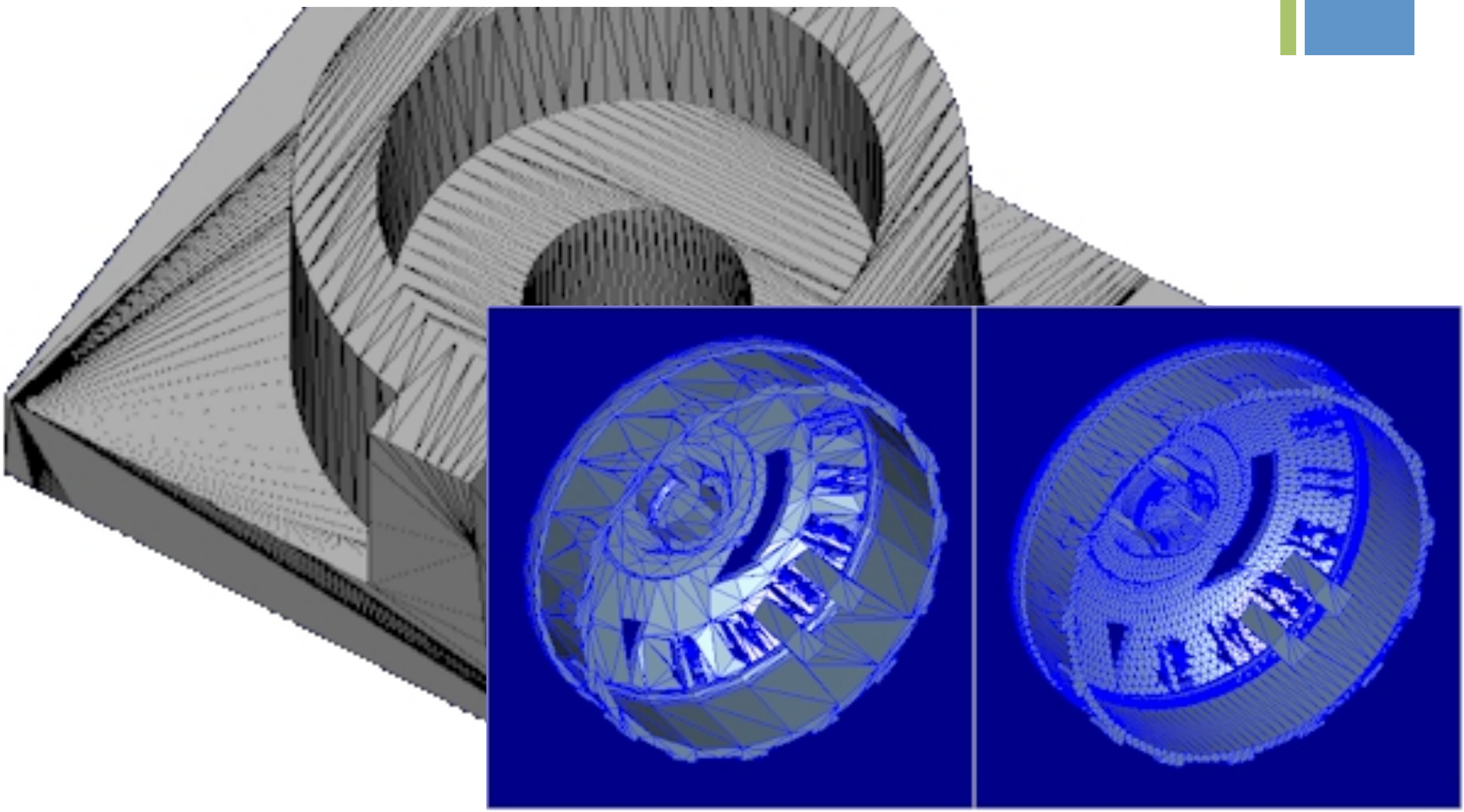
Representing
a sphere





```
solid obj1
  facet normal 1.457591e-01 -9.885599e-01 -3.877669e-02
    outer loop
      vertex 9.614203e+00 4.757629e+00 0.000000e+00
      vertex 7.875000e+00 4.501190e+00 0.000000e+00
      vertex 9.483117e+00 4.764183e+00 -6.598330e-01
    endloop
  endfacet
  facet normal 1.161178e-01 -9.870778e-01 -1.104267e-01
    outer loop
      vertex 9.483117e+00 4.764183e+00 -6.598330e-01
      vertex 7.875000e+00 4.501190e+00 0.000000e+00
      vertex 9.109818e+00 4.782848e+00 -1.219212e+00
    endloop
  endfacet
  facet normal 6.134766e-02 -9.843393e-01 -1.652652e-01
```

Example of *.stl Representation



Existing Formats (1/2)

- 3D PDF
  - Proprietary, closed
- ISO 14649 (STEP-NC)
  - Mostly for NC control, G-Code
- STEP / IGES, SAT, Parasolid
  - Too complex, missing features e.g. no mesostructure
- X3D VRML
  - Mesh, color, texture, lighting

All: no provision for AM, e.g. materials, internal structure

Existing Formats (2/2)

- PLY
  - 3D Scanner data
- 3DS
  - Limited mesh size
- SLC
  - Limited information

All: no provision for AM, e.g. materials, internal structure

New format needed

- Tailor to AM community needs
  - No content constraints
- Retain Community Control
  - Not Proprietary
- Neutral
  - Avoids association with existing companies

Caratteristiche desiderate per un Formato di Interscambio

- simple
- ISO 9000-ish features like product tracking
- Interoperability within different manufacturers
- Compatible with FEA applications
- Identification of parent CAD program
- Restricted number of printings
- Support multiple shells
- Editable ASCII/Text format

Caratteristiche desiderate per un Formato di Interscambio

- Information about build orientation
- Stability/robustness
- No redundancy
- Volume validity
- Lock or encrypt the file with a password
- Ability to put a permanent 'watermark'
- Supporting geometry in native way
- Keep triangle mesh / No triangle mesh

Reaching consensus, adoption

- Non proprietary / open source
- Endorsement by major CAD / Manufacturers
- Use ASTM / Voting
- Backwards compatible (STL)
- Expandable, XML
- Publish for comments / discussion
- Open source software
- Conversion tools
- Limit the scope: Not a CAD model

Current STL

Advantages	Disadvantages
Simple	Geometry leaks
Sequential memory access*	No specified units
Portable	Unnecessary redundancy
	Incompatible with color, multiple materials, etc
	Poor scalability
*Does not require large amounts of RAM, critical in '80s	Lacks auxiliary information

The new proposed format

- AMF
  - Additive Manufacturing Format
  - Additive Manufacturing File

XML

- Meta-format: Format of formats
  - Text based
  - Easy to read/write/parse
  - Existing editing tools
  - Extensible
  - Highly compressible
- Mentioned by a number of constituents
  - E.g. Materialise
  - Based on work by J. Hiller (Cornell)

Addresses needs: Editable / Extensible / Readable / Open / Non proprietary

General Concept

- Part (objects) defined by regions and materials
  - Regions defined by triangular mesh
  - Materials defined by properties/names
- Mesh properties can be specified
  - Color
  - Tolerance
  - Texture
- Materials can be combined
  - Graded materials
  - Microstructure

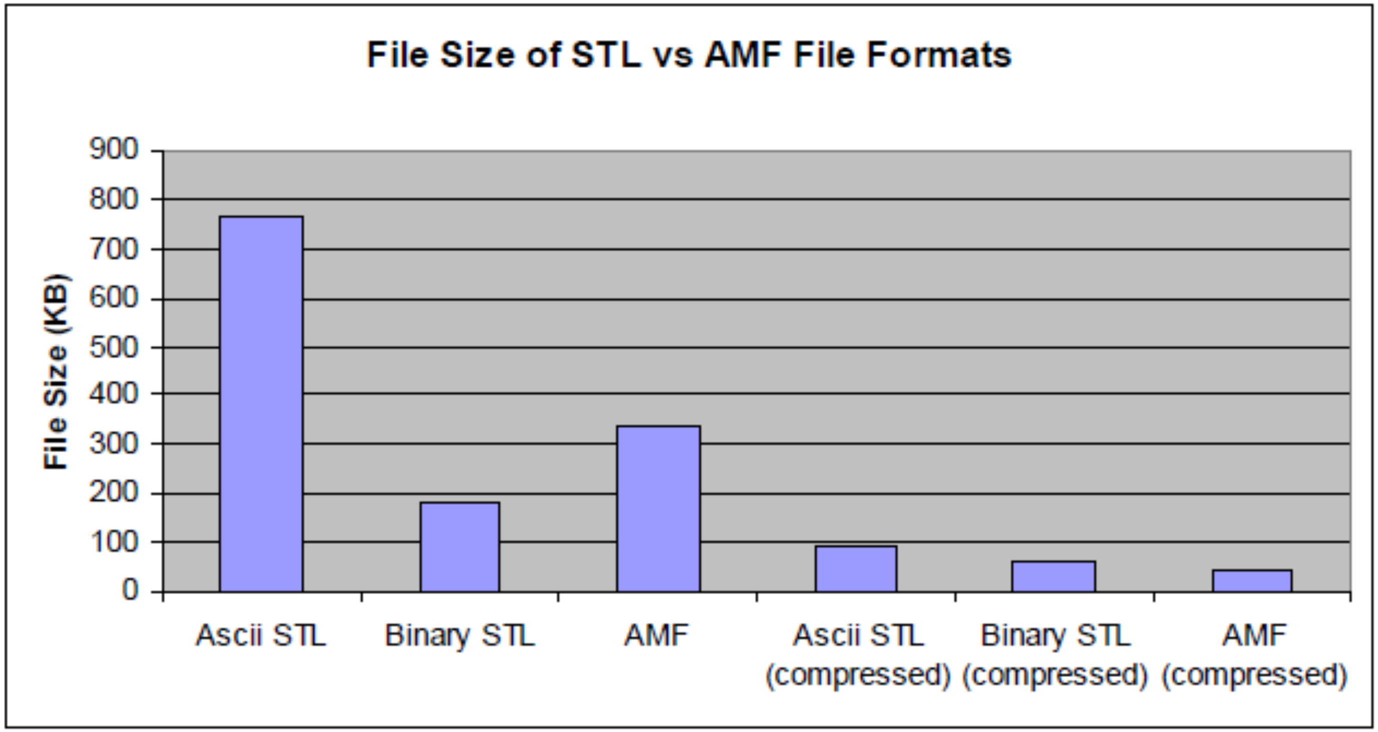
Basic Structure

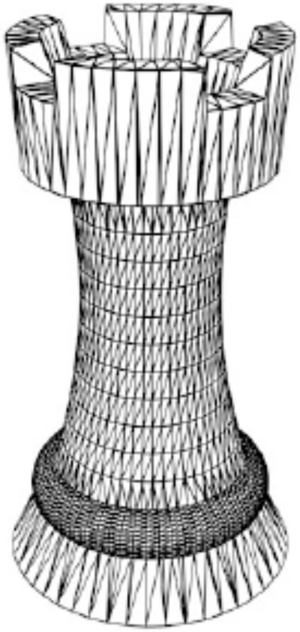
```
<?xml version="1.0"?>
<AMF>
  <Object PrintID = "0" units = "mm">
    <Mesh>
      <Vertices>
        <Vertex VertexID="0">
          <VertexLocation x="0" y="1.332" z="3.715"/>
        </Vertex>
        <Vertex VertexID="1">
          <VertexLocation x="0" y="1.269" z="3.715"/>
        </Vertex>
        ...
      </Vertices>

      <Region FillMaterialID = "0">
        <Triangle V1 = "0" V2 = "1" V3 = "3"/>
        <Triangle V1 = "0" V2 = "1" V3 = "4"/>
        ...
      </Region>
    </Mesh>
  </Object>
</AMF>
```

Addresses needs: Simple / Watertight / Backward Compatible (STL)

Compressibility





Need to look at dependency on # of digits

Addresses needs: Small / Compressible

Multiple Materials

```
<?xml version="1.0"?>
<AMF>
  <Palette>
    <Material MaterialID = "0">
      <Name>StiffMaterial</Name>
    </Material>
    <Material MaterialID = "1">
      <Name>FlexibleMaterial</Name>
    </Material>
  </Palette>

  <Object PrintID = "0" units = "mm">
    <Mesh>
      <Vertices>
        ...
      </Vertices>

      <Region FillMaterialID = "0">
        ...
      </Region>
      <Region FillMaterialID = "1">
        <Triangle V1 = "5" V2 = "6" V3 = "7"/>
        <Triangle V1 = "5" V2 = "7" V3 = "9"/>
        ...
      </Region>
    </Mesh>
  </Object>
</AMF>
```

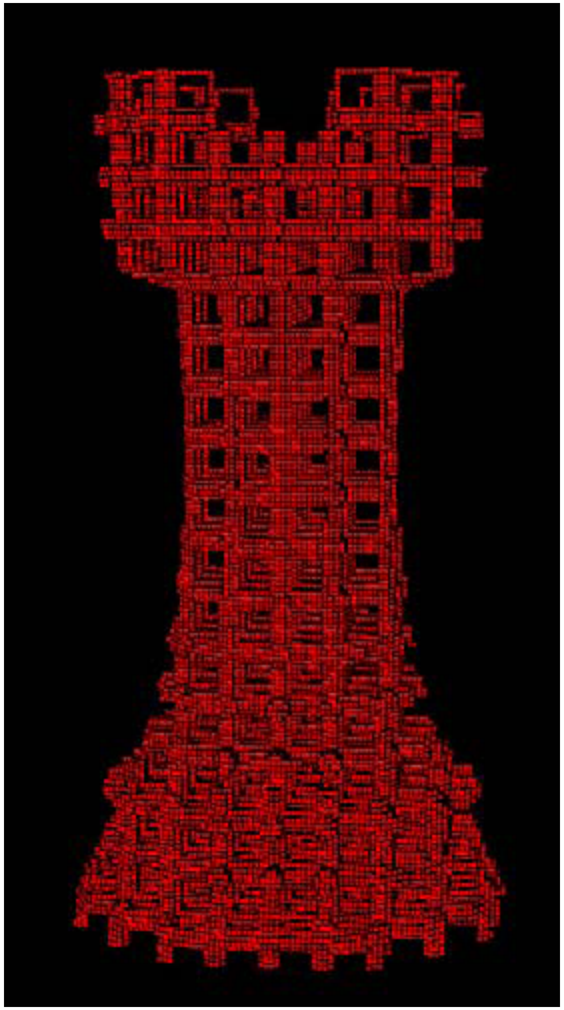
Addresses needs: Multiple Materials, No leaks between regions (shared vertices)

Graded Materials

```
<?xml version="1.0"?>
<AMF>
  <Palette>
    <Material MaterialID = "0">
      <Name>StiffMaterial</Name>
    </Material>
    <Material MaterialID = "1">
      <Name>FlexibleMaterial</Name>
    </Material>
    <Material MaterialID = "2">
      <Name>GradientMaterial</Name>
      <Equation UseMaterialID = "0">0.30*X</Equation>
      <Equation UseMaterialID = "1">0.30*(1-X)</Equation>
    </Material>
  </Palette>

  <Object PrintID = "0" units = "mm">
    ...
  </Object>
</AMF>
```

Microstructure



Addresses needs: Periodic meso/microstructure

+

Material properties

- By manufacturer' s name
  - <Name> **ABS** </Name>
  - <Name>**Tango Black** </Name>
  - <Name>**Nylon 1234** </Name>
- By physical property
  - </Property Type="Elastic Modulus" Value="4E9">
  - </Property Type="Poisson Ratio" Value="1.2">
- External reference (URL)

Addresses needs: Material specifications/libraries

Color and Graphics

- By volumetric region
  - Solid color
- By vertex
  - Specify Vertex color
  - Specify Vertex coordinate in a bitmap

Addresses needs: Color graphics

Color and Graphics

```
<?xml version="1.0"?>
<AMF>
  <Object PrintID = "0" units = "mm">
    <Mesh>
      <ColorFile MapID="0">
        <File>Logo.bmp</File>
      </ColorFile>
      <Vertices>
        <Vertex VertexID="0">
          <VertexLocation x="0" y="1.332" z="3.715"/>
          <VertexMap UseMapID="0" MapXPixel="65"   MapYPixel="87"/>
        </Vertex>
        <Vertex VertexID="1">
          <VertexLocation x="0" y="1.269" z="3.715"/>
          <VertexMap UseMapID="0" MapXPixel="64" MapYPixel="87"/>
        </Vertex>
        <Vertex VertexID="2">
          <VertexLocation x="0" y="1.310" z="3.587"/>
          <VertexMap UseMapID="0" MapXPixel="32" MapYPixel="10"/>
        </Vertex>
        ...
      </Vertices>

      <Region FillMaterialID = "0">
        <Color R = "0" G = "0" B = "0.5"/>
        <Triangle V1 = "0" V2 = "1" V3 = "2"/>
        <Triangle V1 = "0" V2 = "1" V3 = "4"/>
        ...
      </Region>
    </Mesh>
  </Object>
</AMF>
```

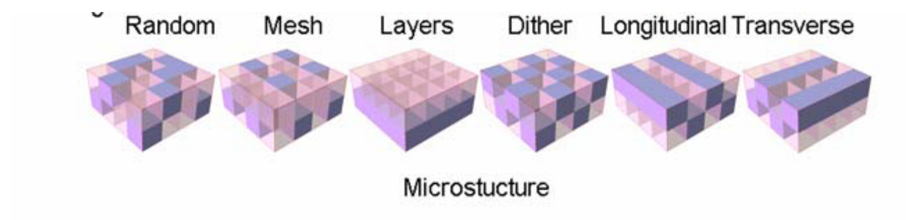
Tolerances

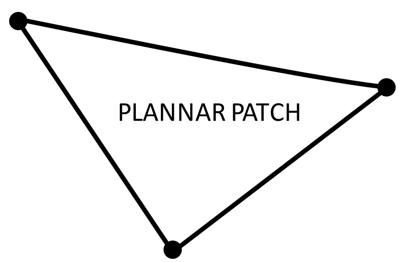
- By volumetric region
  - Nominal tolerance
  - Allowed variation from original volume
- By vertex
  - Specify point tolerance (?)
  - Point to point

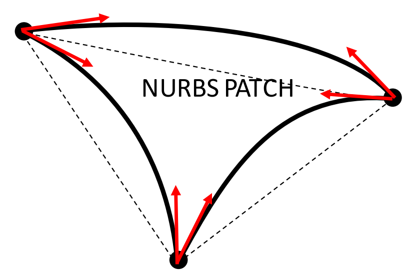
Addresses needs: Tolerance

Non-meshed geometry?

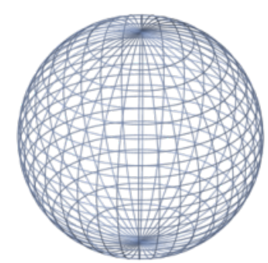
- Other representations are not mutually exclusive
- **Voxel maps**
  - For digital/inkjet microstructure
- **NURBS**
  - Add slope vectors to some triangle mesh edges
  - Other STEP types?
- **Functional Representations**
  - implicit equations





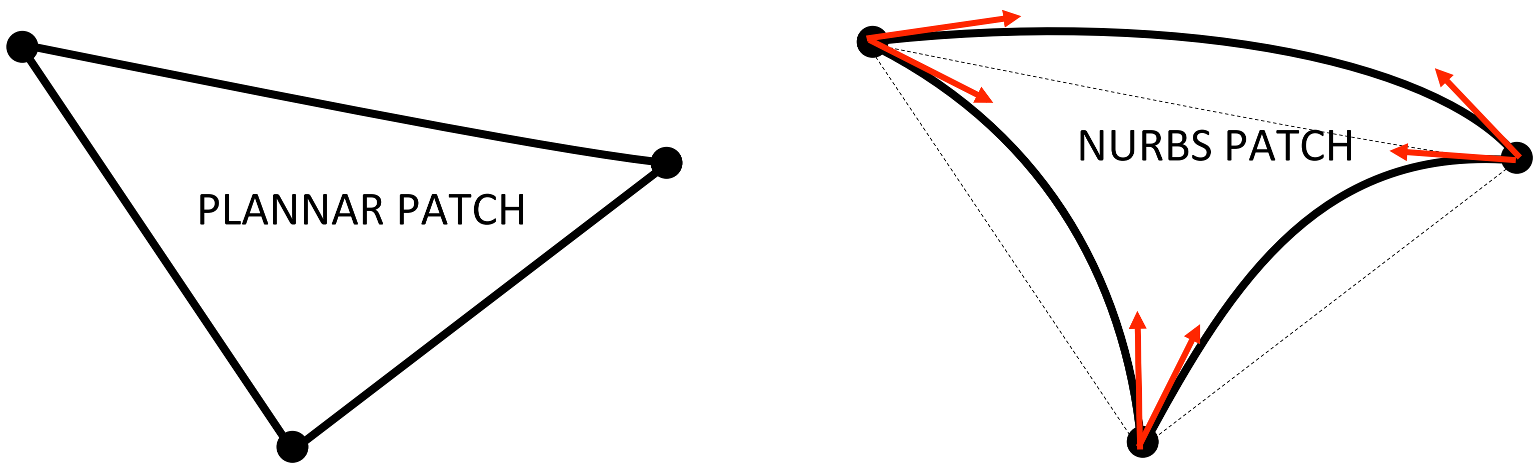



```
<?xml version="1.0"?>
<AMF>
  <Object PrintID = "0" units = "mm">
    <FRep MaterialID = "0">
      <GeometryEquation>
        <![CDATA[X^2+Y^2+Z^2-4 <= 0 & Z >= 0]]>
      </GeometryEquation>
    </FRep>
  </Object>
</AMF>
```



Nurbs patch

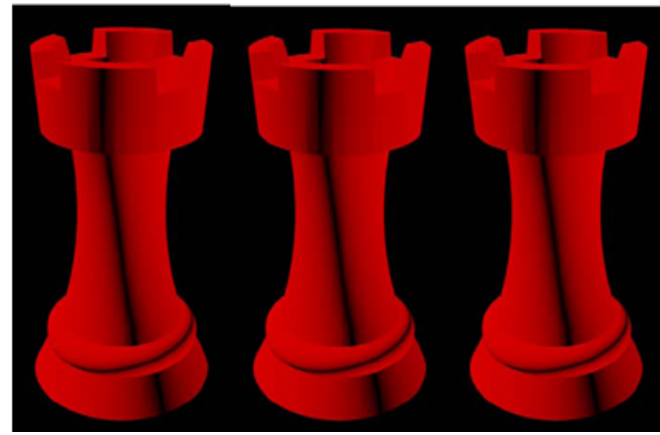
- Optionally add slope vectors to some triangle mesh edges to allow for very accurate geometry.
  - Perfect sphere can be made with ~20 patches



+

Print Constellation

- Print orientation
- Duplicated objects
- Sets of different objects
- Efficient nesting
- Hierarchical



Metadata

<Metadata>
<Datum ID=“Author” Data=“John Doe”></Datum>
<Datum ID=“Company” Data=“…”></Datum>
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+

Encryption

<Metadata>

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<Datum ID="Encryption" Data="Prompt"></Datum>

</Metadata>

```
<Mesh>
  <Vertices>
    <Vertex VertexID="0">
      <VertexLocation x="0" y="1.332" z="3.715"/>
    </Vertex>
    <Vertex VertexID="1">
      <VertexLocation x="0" y="1.269" z="3.715"/>
    </Vertex>
```

Key garbles vertex coordinates (e.g. using XOR); need key to un-garble

+

Watermark / Copyright

<Metadata>
<Datum ID=“Author” Data=“John Doe”></Datum>
<Datum ID=“Company” Data=“…”></Datum>
<Datum ID=“Description” Data=“…”></Datum>
<Datum ID=“Comment” Data=“…”></Datum>
<Datum ID=“Copyright” Data=“Owner”></Datum>
</Metadata>

```
<Mesh>
  <Vertices>
    <Vertex VertexID="0">
      <VertexLocation x="0" y="1.332" z="3.715"/>
    </Vertex>
    <Vertex VertexID="1">
      <VertexLocation x="0" y="1.269" z="3.715"/>
    </Vertex>
```

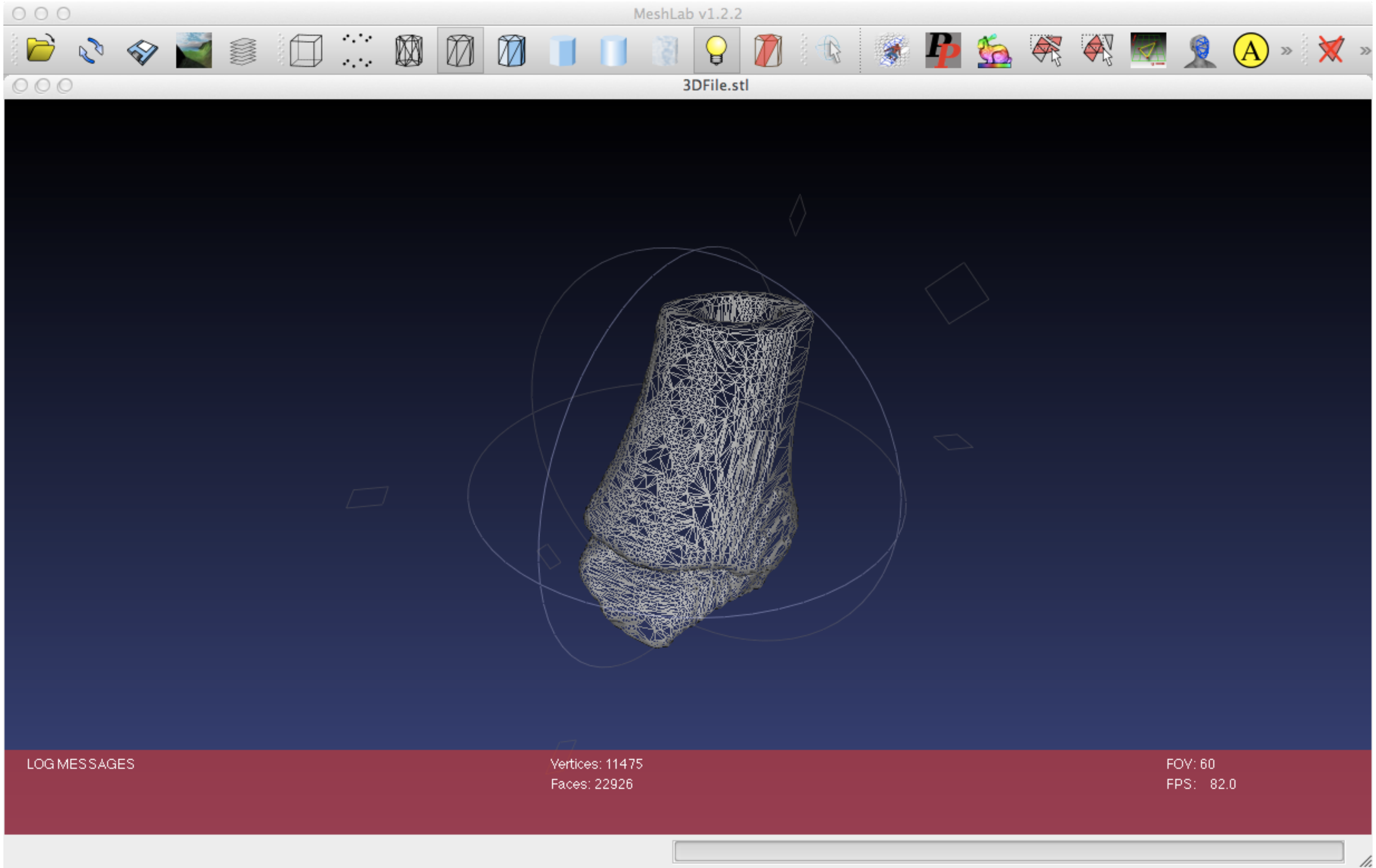
Copyright name garbles vertex coordinates (e.g. using XOR); copyright must be present to un-garble

Other features

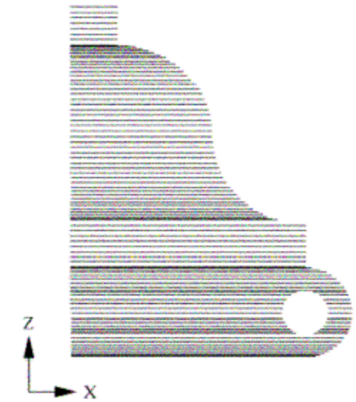
- URL can be used in lieu of material data to allow for external libraries
- Validation checksums
  - E.g. Original vs. actual part/region volumes
- Automatic error checking
  - Readers/writers must check for intact topology, e.g.
    - All nodes referenced by at least 3 triangles
    - All edges referenced exactly twice per region

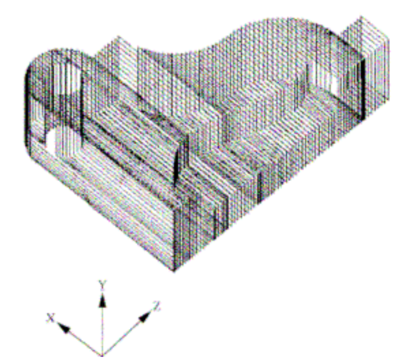
MeshLab

http://meshlab.sourceforge.net



DA CAD A CAM





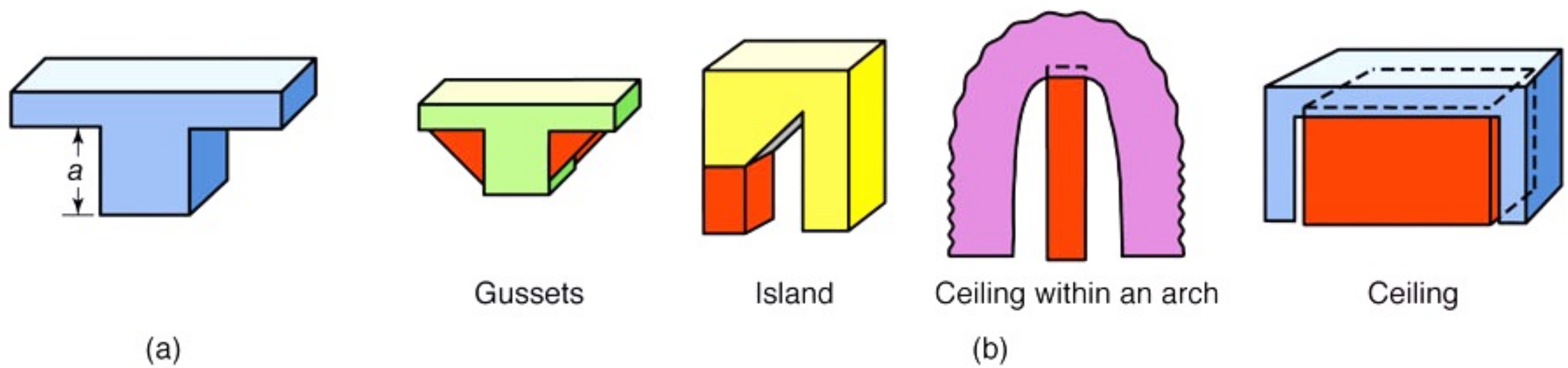
Processing of *.stl Files

- After the CAD system has generated *.stl file, it can be passed to the SLA machine (or any SFM machine)
- Machine then processes the *.stl file, slicing it into many thin layers stacked on one another. The resulting files are called slice files.
- The shapes of the slices represent cross sections
- In SLA (and in many SFM processes) thick solid sections of material are often removed and replaced with cross hatching
- Thus SLA (& many SFM) parts are usually hollow, with cross hatching on the inside to add strength/stability

Support material

- Some solid freeform fabrication techniques use two materials in the course of constructing parts.
- The first material is the part material and the second is the support material (to support overhanging features during construction).
- The support material is later removed by heat or dissolved away with a solvent or water.

Support Materials and Structures



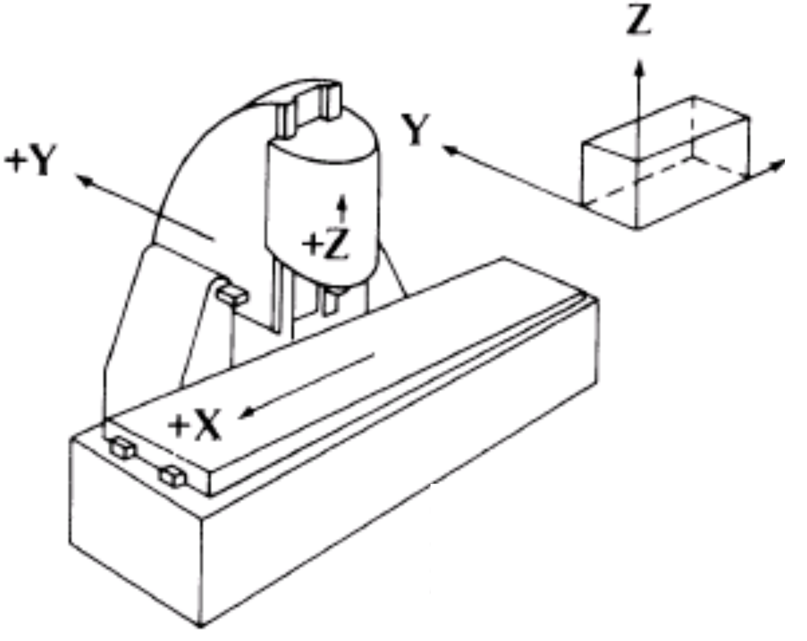
(a) A part with a protruding section which requires support material. (b) Common support structures used in rapid-prototyping machines. *Source:* P. F. Jacobs, *Rapid Prototyping & Manufacturing: Fundamentals of Stereolithography.* Society of Manufacturing Engineers, 1992.

Metodi di patterning

- Vector
- Raster
- Projection

Basic Machine Axes: 3 axis

- Cartesian Robot: 3 axis
  - X – axis (table left and right)
  - Y – axis (table in and out)
  - Z – axis (usually the extruder axis)



G-CODE

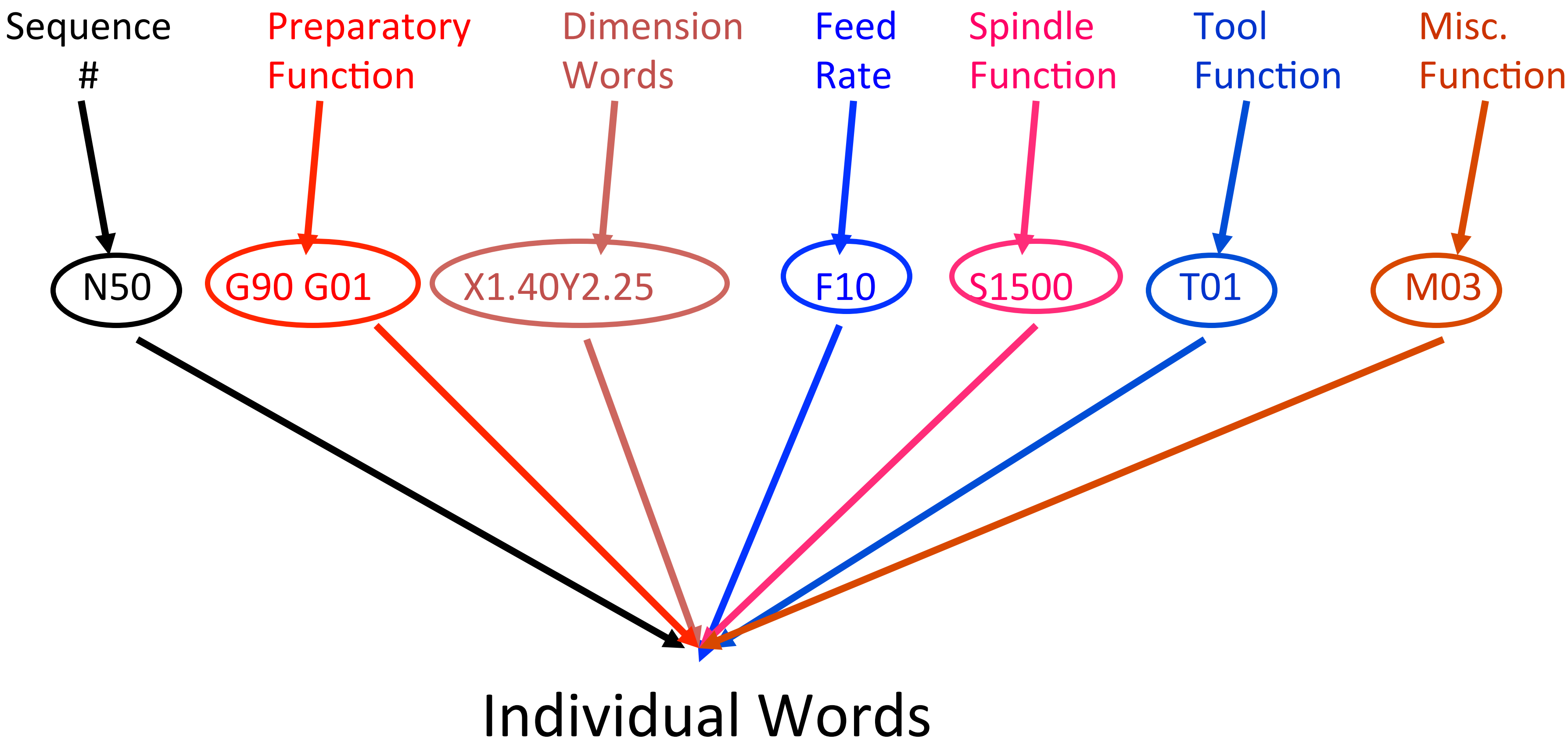
- G – Code Programming
- Originally called the "Word Address" programming format.
- Processed one line at a time sequentially.

Word address format

- Word address was developed as a tape programming format.
  - Another name for "word address" is "variable block" format, so named because the program lines (blocks) may vary in length according to the information contained in them.
  - Earlier tape formats required an entry for all possible machine registers. In these earlier formats, a zero was programmed as a null input if the register values were to be unaffected, but in work address, the blocks need only contain necessary information. Although developed as a tape format, word address is used as the format for manual data input on many CNC machines.

- <u>Addresses</u>
  - The block format for word address is as follows:
  - N … G … X … Y … Z … I … J … K … F … H … H … S … T … M …
  - Only the information needed on a line need be given. Each of the letters is called an address (or word)

Common Format of a Block



Word address

- Reserved Code Words Worksheet
  - N – Sequence or line number
  - G – Preparatory function
  - …

- Dimension Words:
  - X
  - Y
  - Z

Word Address 1/3

- N – Sequence or line number
  - A tag that identifies the beginning of a block of code. N numbers are ignored by the controller during the program execution. It is used by operators to locate specific lines of a program when entering data or verifying the program operation.

- G – Preparatory function
  - G words specify the mode in which the milling machine is to move along its programmed axes. Preparatory functions are called prep functions or, more commonly **G codes**

Word Address 2/3

- Dimension Words
  - X – Distance or position in X direction
  - Y – Distance or position in Y direction
  - Z – Distance or position in Z direction

- M – Miscellaneous functions
  - M words specify CNC machine functions not related to dimensions or axial movements.

Word Address 3/3

- F – Feed rate (inches per minute or millimeters per minute)
  - Rate at which cutting tool moves along an axis.
- S – Spindle speed (rpm – revolutions per minute)
  - Controls spindle rotation speed.
- T – Tool number
  - Specifies tool to be selected.

G Word

- G words or codes tell the machine to perform certain functions. Most G words are modal which means they remain in effect until replaced by another modal G code.

Common G Codes

- G00 – Rapid positioning mode
  - Tool is moved along the shortest route to programmed X,Y,Z position. Usually NOT used for cutting.
- G01 – Linear Interpolation mode
  - Tool is moved along a straight-line path at programmed rate of speed.

- G02 – Circular motion clockwise (cw)
- G03 – Circular motion counter clockwise (ccw)

M Word

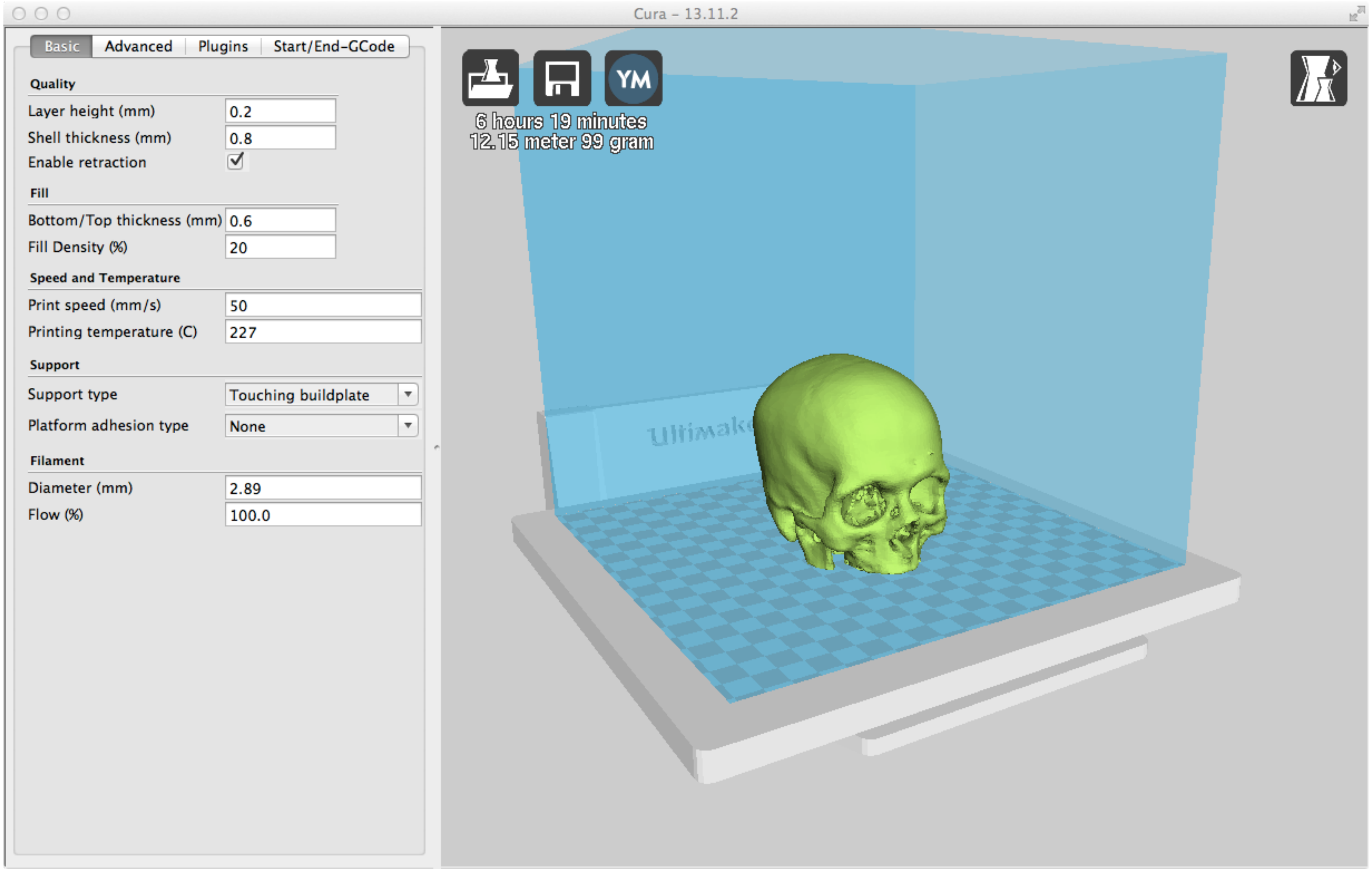
- M words tell the machine to perform certain machine related functions, such as: turn spindle on/off, coolant on/off, or stop/end program.

Esempio G-Code

```
;Generated with Cura_SteamEngine 13.11.2
M109 T0 S227.000000
T0
;Sliced ?filename? at: Tue 26-11-2013 17:33:05
;Basic settings: Layer height: 0.2 Walls: 0.8 Fill: 20
;Print time: #P_TIME#
;Filament used: #F_AMNT#m #F_WGHT#g
;Filament cost: #F_COST#
G21        ;metric values
G90        ;absolute positioning
M107       ;start with the fan off
G28 X0 Y0  ;move X/Y to min endstops
G28 Z0     ;move Z to min endstops
G1 Z15.0 F?max_z_speed? ;move the platform down 15mm
G92 E0              ;zero the extruded length
G1 F200 E3             ;extrude 3mm of feed stock
G92 E0              ;zero the extruded length again
G1 F9000
M117 Printing...

;Layer count: 179
;LAYER:0
M107
G0 F3600 X87.90 Y78.23 Z0.30
;TYPE:SKIRT
G1 F2400 E0.00000
G1 F1200 X88.75 Y77.39 E0.02183
G1 X89.28 Y77.04 E0.03342
G1 X90.12 Y76.69 E0.05004
G1 X90.43 Y76.63 E0.05591
G1 X91.06 Y76.37 E0.06834
...
```

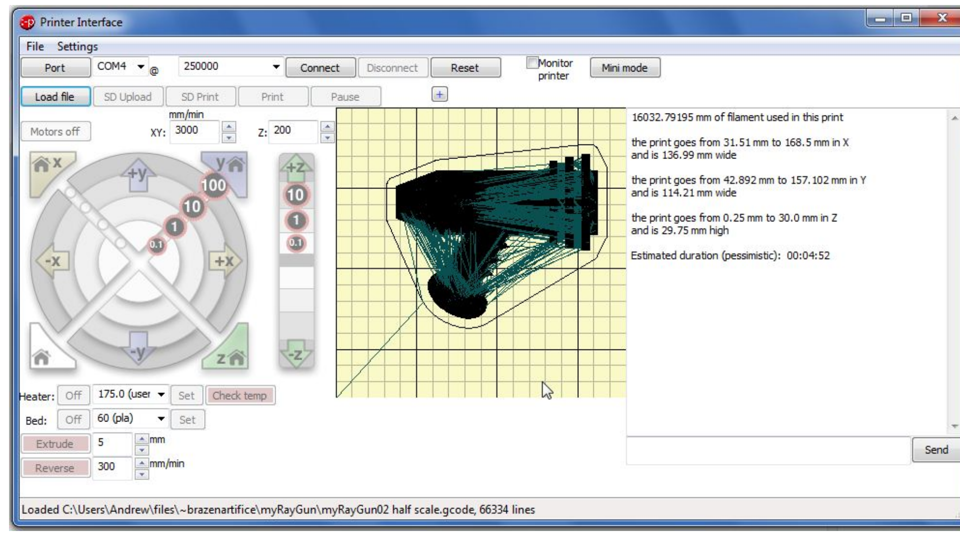
Cura



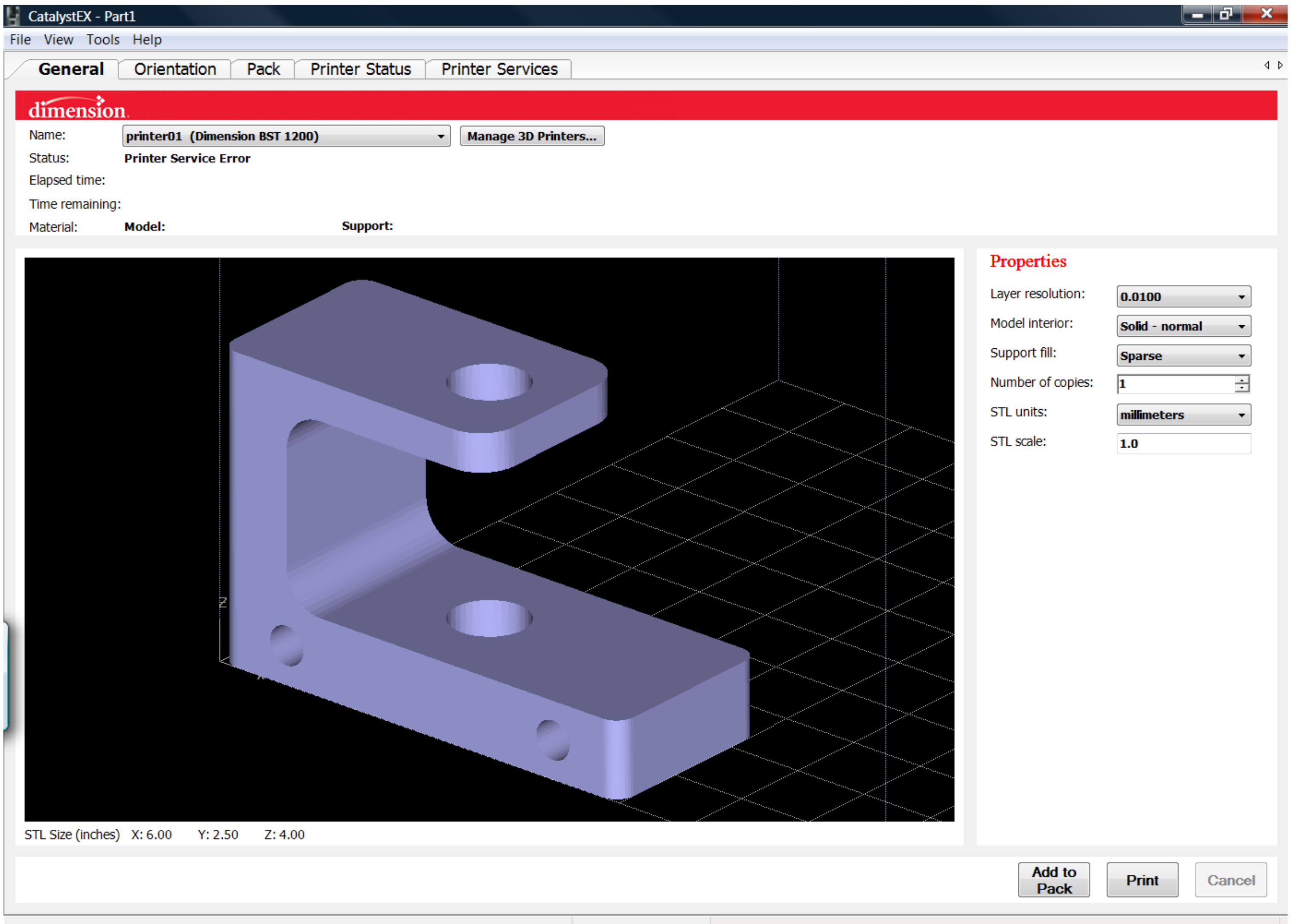
Cura – 13.11.2
Basic
Advanced
Plugins
Start/End-GCode
Quality
Layer height (mm)
0.2
Shell thickness (mm)
0.8
Enable retraction
Fill
Bottom/Top thickness (mm)
0.6
Fill Density (%)
20
Speed and Temperature
Print speed (mm/s)
50
Printing temperature (C)
227
Support
Support type
Touching buildplate
Platform adhesion type
None
Filament
Diameter (mm)
2.89
Flow (%)
100.0
YM
6 hours 19 minutes
12.15 meter 99 gram

Slic3r


Slic3r
G-code generator for 3D printers
Slic3r
Plater
Print Settings
Filament Settings
Printer Settings
Name
Copies
Scale
Add...
Autoarrange
Export G-code
Delete
Delete All
Export STL...
Print settings:
Filament:
Printer:


Printer Interface
File
Settings
Port
COM4
250000
Connect
Disconnect
Reset
Monitor printer
Mini mode
Load file
SD Upload
SD Print
Print
Pause
Motors off
mm/min
XY: 3000
Z: 200
16032.79195 mm of filament used in this print
the print goes from 31.51 mm to 168.5 mm in X and is 136.99 mm wide
the print goes from 42.892 mm to 157.102 mm in Y and is 114.21 mm wide
the print goes from 0.25 mm to 30.0 mm in Z and is 29.75 mm high
Estimated duration (pessimistic): 00:04:52
Heater:
Off
175.0 (user
Set
Check temp
Bed:
Off
60 (pla)
Set
Extrude
5
mm
Reverse
300
mm/min
Send
Loaded C:\Users\Andrew\files\~brazenartifice\myRayGun\myRayGun02 half scale.gcode, 66334 lines

Stratasys Catalyst



Stratasys Catalyst