# Support-less Horizontal Filament-stacking by Layer-less FDM

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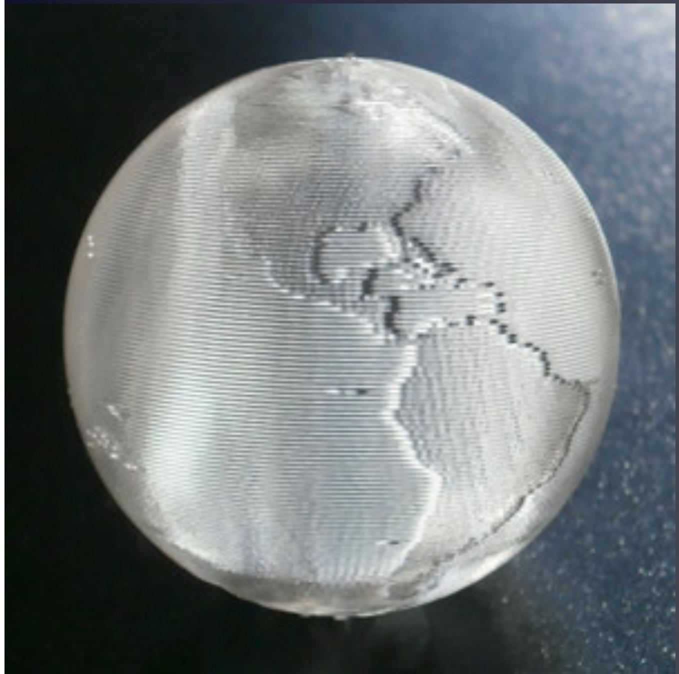
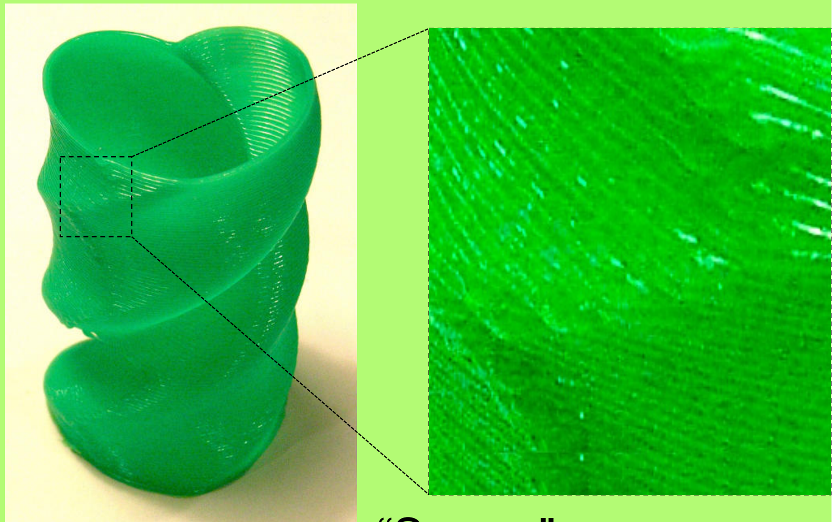


# Introduction

- ► **Conventional AM methods stack material vertically and layer-by-layer.**
- ► **Two problems are caused by conventional methods.**
  - ■ Difficult to create objects with low-angle overhang without support material.
  - ■ "Seams" are easily generated between layers.
- ► **This paper proposes "the helical/ spiral printing method".**
  - ■ It solves the above problems.
  - ■ It enables generating various shapes and texture mapping on the surface.

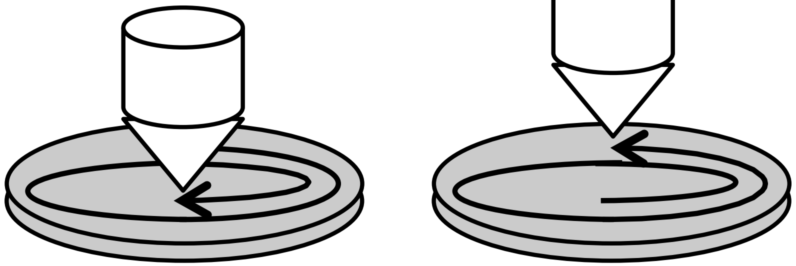
Objects with low-angle overhang (shallow plate and empty sphere)

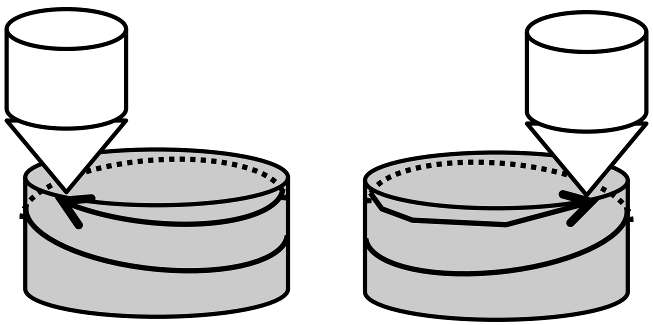


"Seams"

# Proposal: Helical/spiral Printing Method

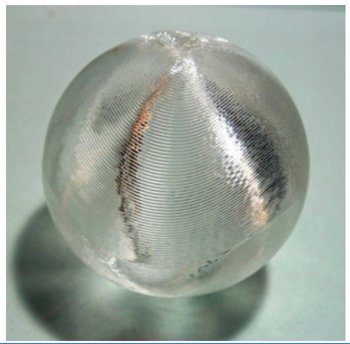
- ► **This method solves the problems by printing objects helically or spirally (instead of printing layer-by-layer).**


Spiral printing


Helical printing

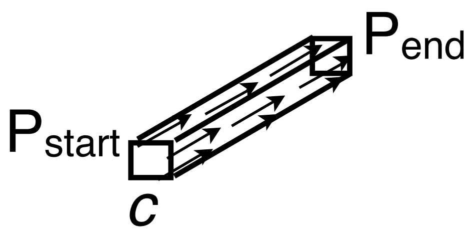
  - ■ Print directions may be *skewed* and can *shake* up and down.
  - ■ Print directions can be *specified* by the designer.

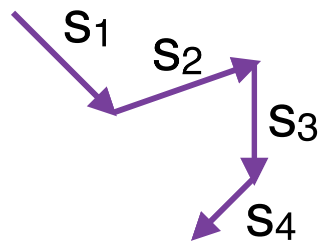
- ► **This method enables …**
  - ■ Reduction of seams (by reducing non-printing head motions).
  - ■ Low-angle overhang without support.
  - ■ Generation of a thin (single-layer) and strong structure.



# Representation of Object Models

- **New representation is required for this method because**
  - conventional CAD models cannot be used, and
  - "direction" is specified for each part of models in this representation.
- **A model is represented by a sequence of directed *strings*.**
  - Directed **string**: ($P_{start}$, $P_{end}$, *c*, *v*)
  - $P_{start}$ : tail
  - $P_{end}$ : head
  - *c* : cross section of string
  - *v* : printing speed (optional)

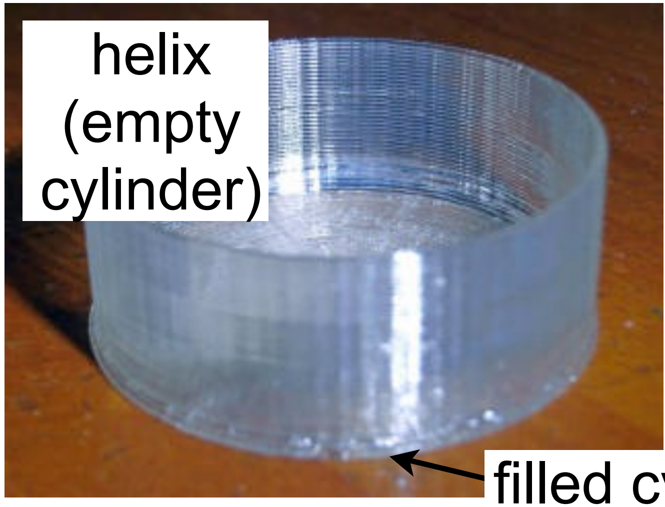



- **Models must be "printable".**
  - *c* (and *v*) must be properly defined for printability.

# Deformation Method

- **How can this method print various shapes.**
  - They can be generated by “deformation”
- **“Deformation” generates various shapes and directions in a generative way while preserving printability.**
- **Original shape and Deformed shapes**




deformation

# Description of Deformations*

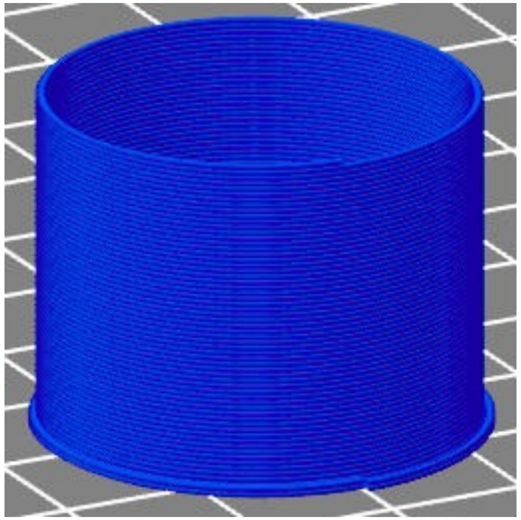
- **Deformation using Descartes coordinates**
  **deform_xyz(*fd*(*x*, *y*, *z*), *fc*(*c*, *x*, *y*, *z*), *fv*(*v*, *x*, *y*, *z*))**
  - *fd* : mapping **location (*x*, *y*, *z*)** to (*x'*, *y'*, *z'*).
  - *fc* : mapping **cross section *c*** at (*x*, *y*, *z*) to *c'* at (*x'*, *y'*, *z'*).
  - *fv* : mapping **printing speed *v*** at (*x*, *y*, *z*) to *v'* at (*x'*, *y'*, *z'*).

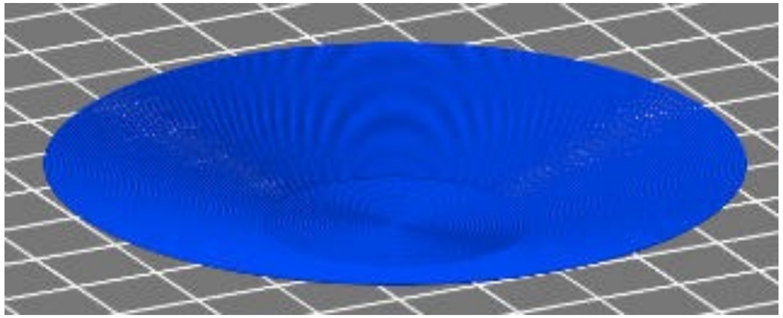
- **Deformation using cylinder coordinates**
  **deform_cylinder(*fd*(*r*, *θ*, *z*), *fc*(*c*, *r*, *θ*, *z*), *fv*(*v*, *r*, *θ*, *z*))**
  - *fd* : mapping **location** (*r*, *θ*, *z*), which is expressed in cylinder coordinates, to (*r'*, *θ'*, *z'*).
  - *fc* : mapping **cross section *c*** at location (*r*, *θ*, *z*) to *c'* at (*r'*, *θ'*, *z'*).
  - *fv* : mapping **printing speed *v*** at location (*r*, *θ*, *z*) to *v'* at (*r'*, *θ'*, *z'*).

- **Deformations must preserve "printability".**

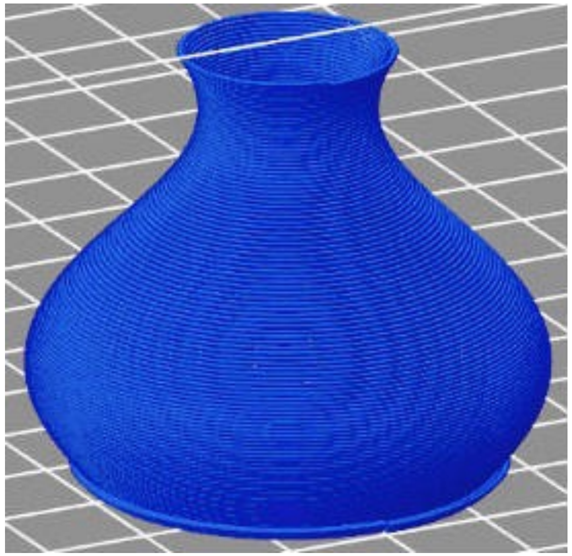
# Deformation: Examples

- **Dish:**
  deform_cylinder(
  *fdd*(*r*, *θ*, *z*), *fcd*(*c*, *r*, *θ*, *z*), *fvd*(*v*, *r*, *θ*, *z*))
  where *fdd*(*r*, *θ*, *z*) = (*r* + 1.05 *z*, *θ*, 0.3 *z*).





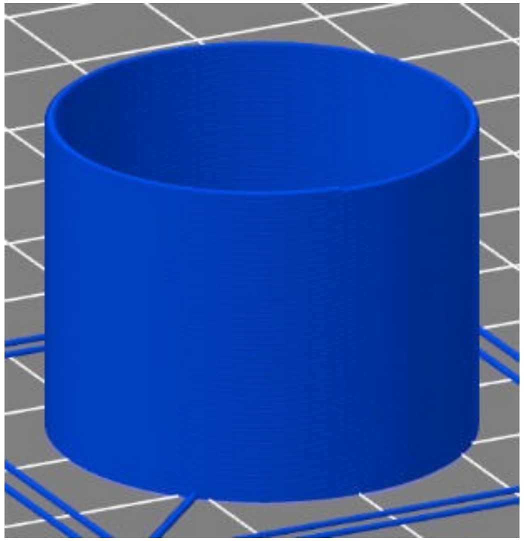
Displayed by Repetier-Host

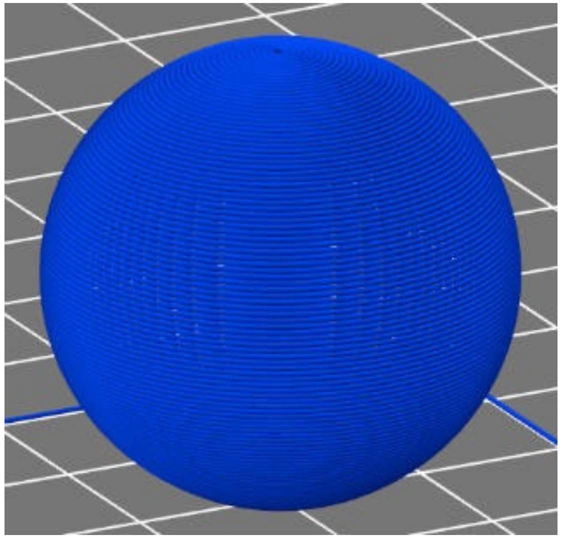


- **Vase:**
  deform_cylinder(
  *fdp*(*r*, *θ*, *z*), *fcp*(*c*, *r*, *θ*, *z*), *fvp*(*v*, *r*, *θ*, *z*))
  where *fdp*(*r*, *θ*, *z*) =
  (*r* (0.8 + 0.4 sin(*z* / 8 + 6.5)), *θ*, *z*)

# Deformation: Examples (cont'd)

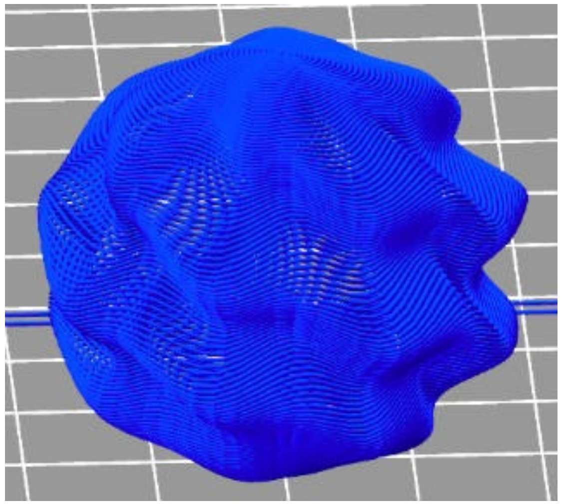
► **Sphere:**
deform_cylinder(*fds*(*r*, *θ*, *z*), *fvs*(*v*, *r*, *θ*, *z*), *fcs*(*c*, *r*, *θ*, *z*))
where *fds*(*r*, *θ*, *z*) =
(*Radius* * sin(*z* / *cylinderHeight*), *θ*, *r* – *Radius* * cos(*z* / *cylinderHeight*))





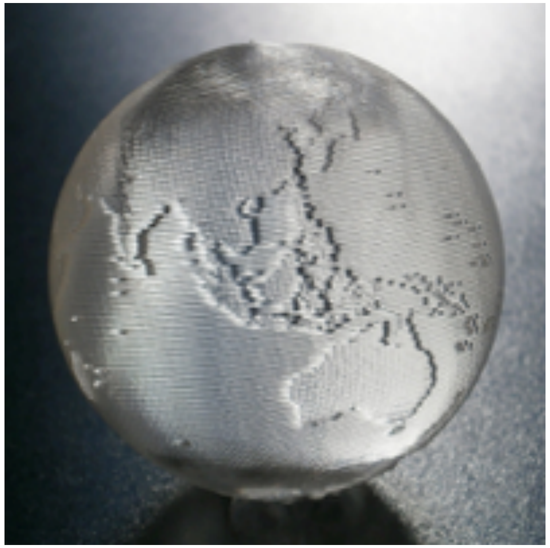
Another deformation

Modulation

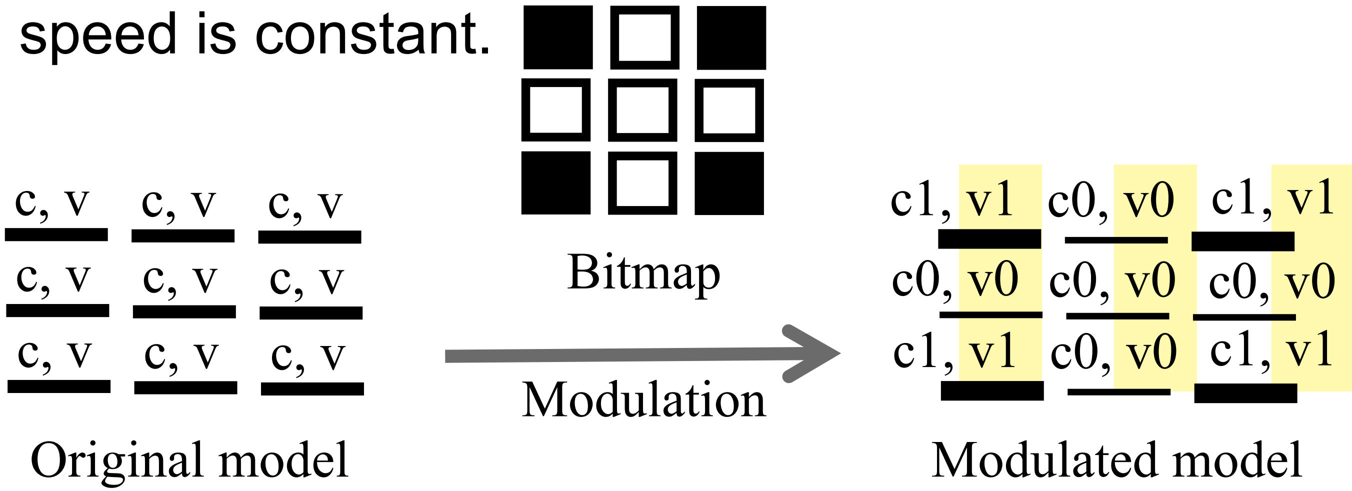


# Additional Technique 1: Texture Mapping

- **A method for mapping textures, characters, or pictures on the surface of printed objects is proposed.**
  - Textures are expressed by difference of cross-sections.



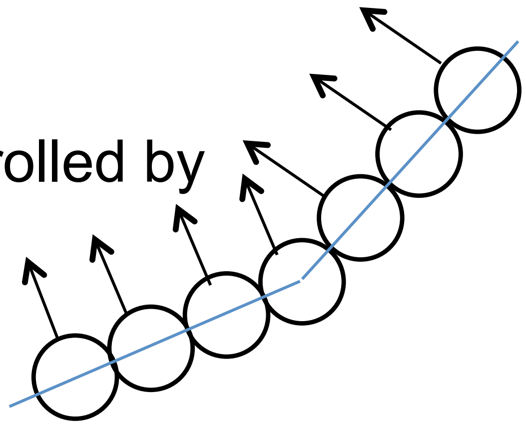
- **Cross-sections of strings are modulated *by changing head-motion speed*.**
  - Extrusion speed is constant.



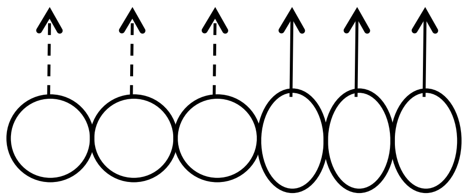

  - Not by changing extrusion speed because it is difficult to change extrusion speed quickly.

# Additional Technique 2: Light-reflection Control

- ► **Brilliantly shining objects can be created by transparent filaments such as clear PLA.**
- ► **It is enabled by controlling the amount and the direction of reflection.**
  - ■ Reflection controlled by overhang angle



  - ■ Reflection controlled by filament density

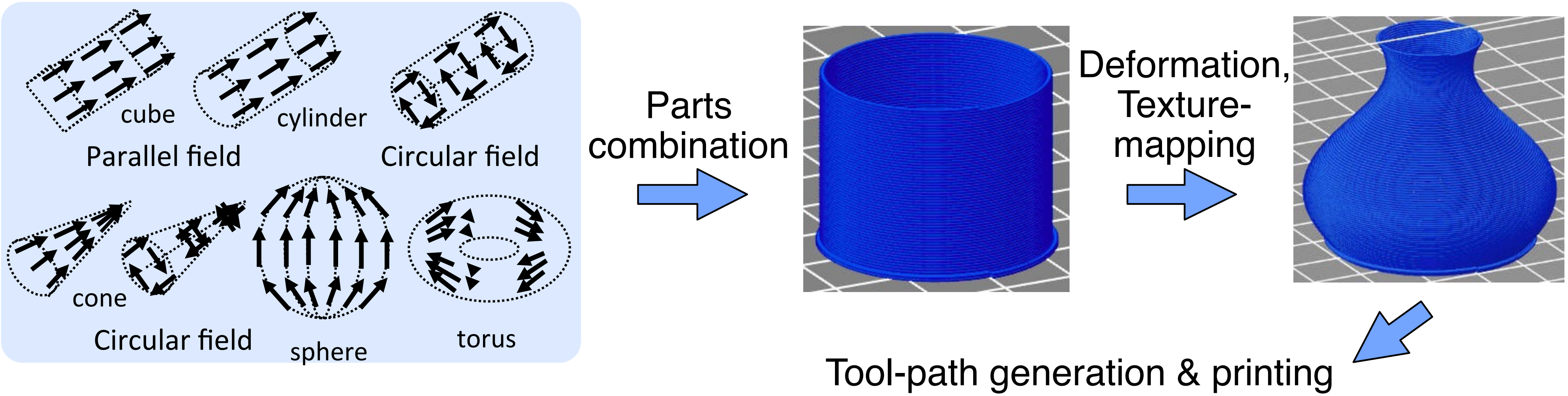



# CAD-based Modeling/Manufacturing Method

## ► Conventional methods (CAD & slicing) cannot be used.

- Conventional method is layer-based.
- Printing directions should be specified at design time.

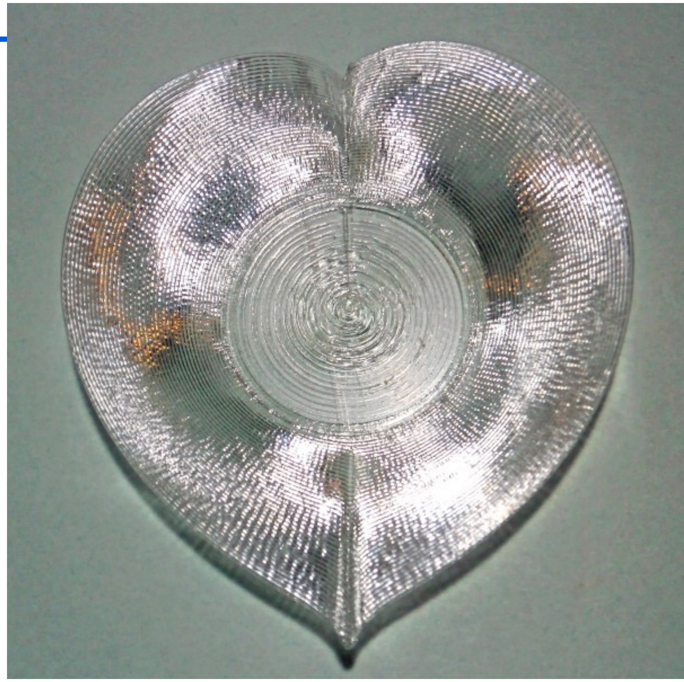
## ► CAD & "slicer" should be "directed-part based".

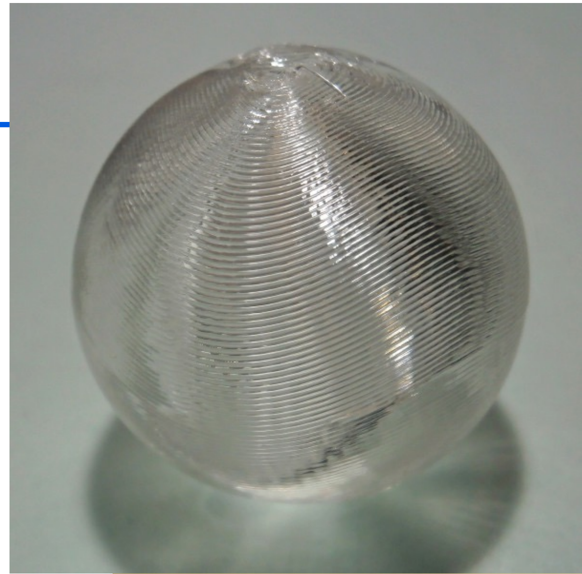



## ► A preliminary tool "draw3dp.py" is being developed.

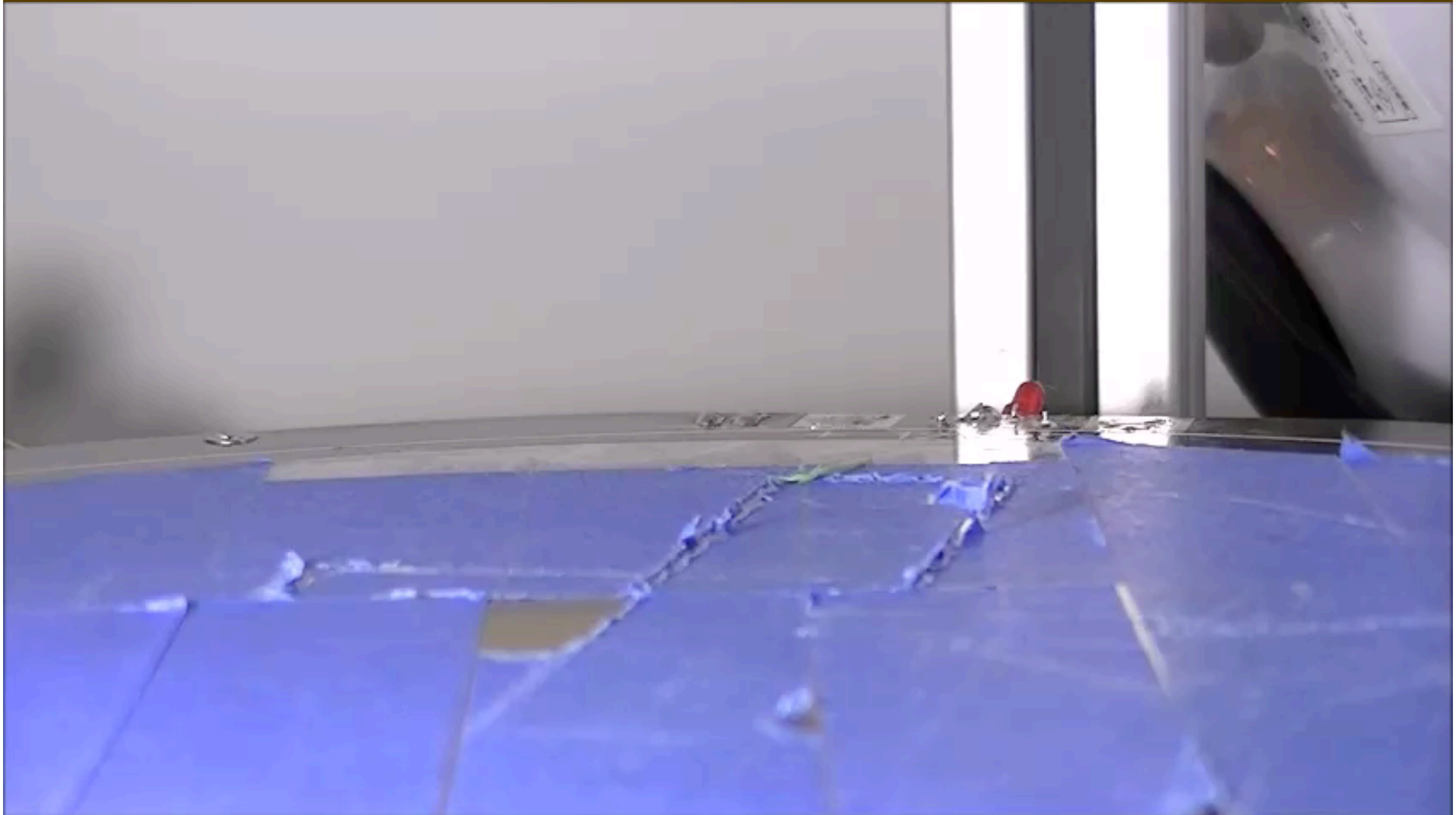
- Python API, "draw3dp.py", is publicly available.
- Parts are combined procedurally.
- Deformation and texture-mapping are also described procedurally.
- Programmers can program other operations.

# Print Results






# Printing Process of Globe



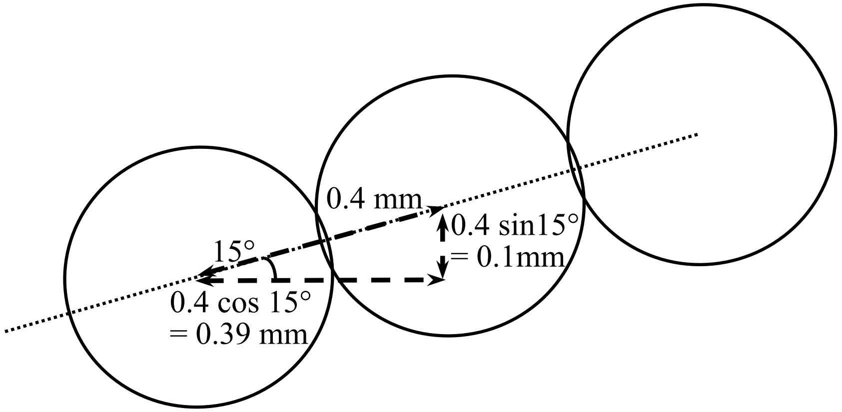
8 times faster.  YouTube  http://youtu.be/YWx1vqig2-o

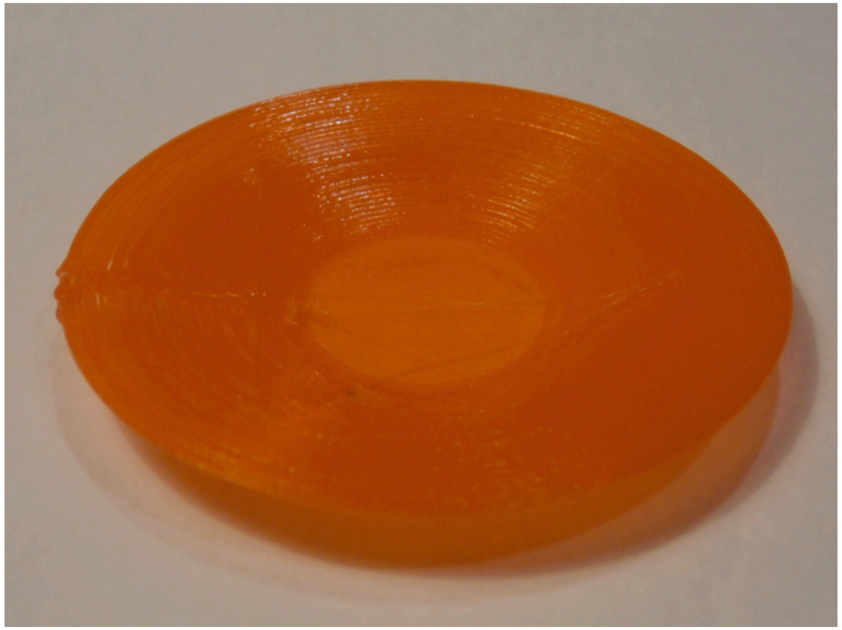
# Summary and Conclusion

- **The proposed helical/spiral printing method solves two problems.**
  - It enables printing objects with low-angle overhang without support material.
  - It eliminates “seams” between layers because it is layer-less.
- **Deformation enables creation of various shapes.**
- **Several additional techniques used with the helical/ spiral printing method were proposed.**
  - Texture mapping enables creation of various textures (or characters or pictures) on the surface of printed objects.
  - Light-reflection control enables brilliantly shining objects.
- **A CAD-based methodology for the proposed printing method was also proposed.**

# Printing Shallow Plates by a Conventional FDM*

- ► **Shallow plates can be printed by "hacking" a conventional printing method.**
  - ■ Filament can be stacked nearly horizontally by "cheating" slicers.



- ► **However, "seams" cannot be avoided by this method.**