Self-organized 3D-printing Patterns Simulated by Cellular Automata

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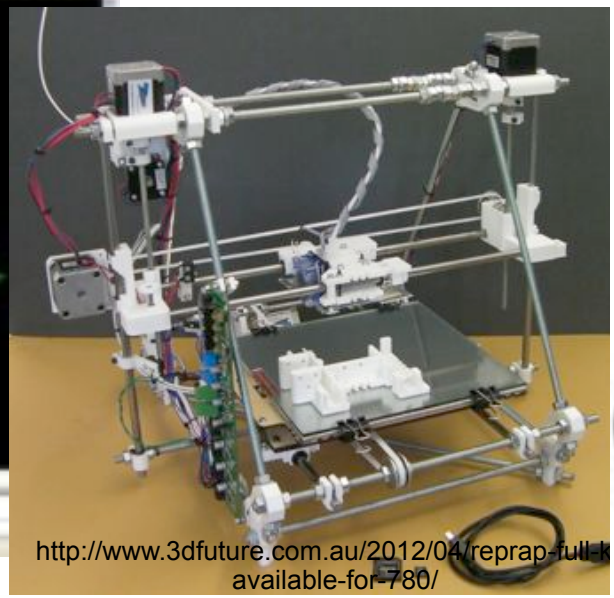
Conventional 3D printing technology

- **Objects are designed by using 3D CAD.**
- **3D objects are printed layer by layer.**
- **Cheap "FDM" 3D printers are widely used.**
  - "FDM" means fused deposition modeling

Autodesk (CAD software)

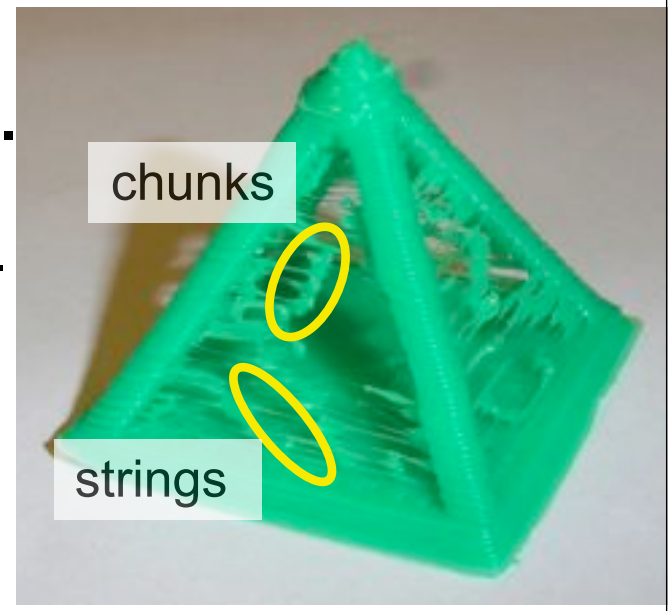


Reprap

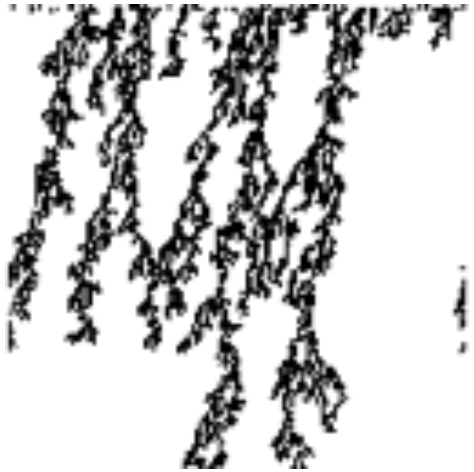
Rostock MAX

Observations and Interpretations

- **3D printers can generate "naturally-randomized" self-organized patterns.**
  - Self-organized patterns such as *chunks* or *strings* are sometimes generated.
  - Printing conditions and process including nozzle temperature, extrusion process, air motion, etc., are fluctuated (randomized).

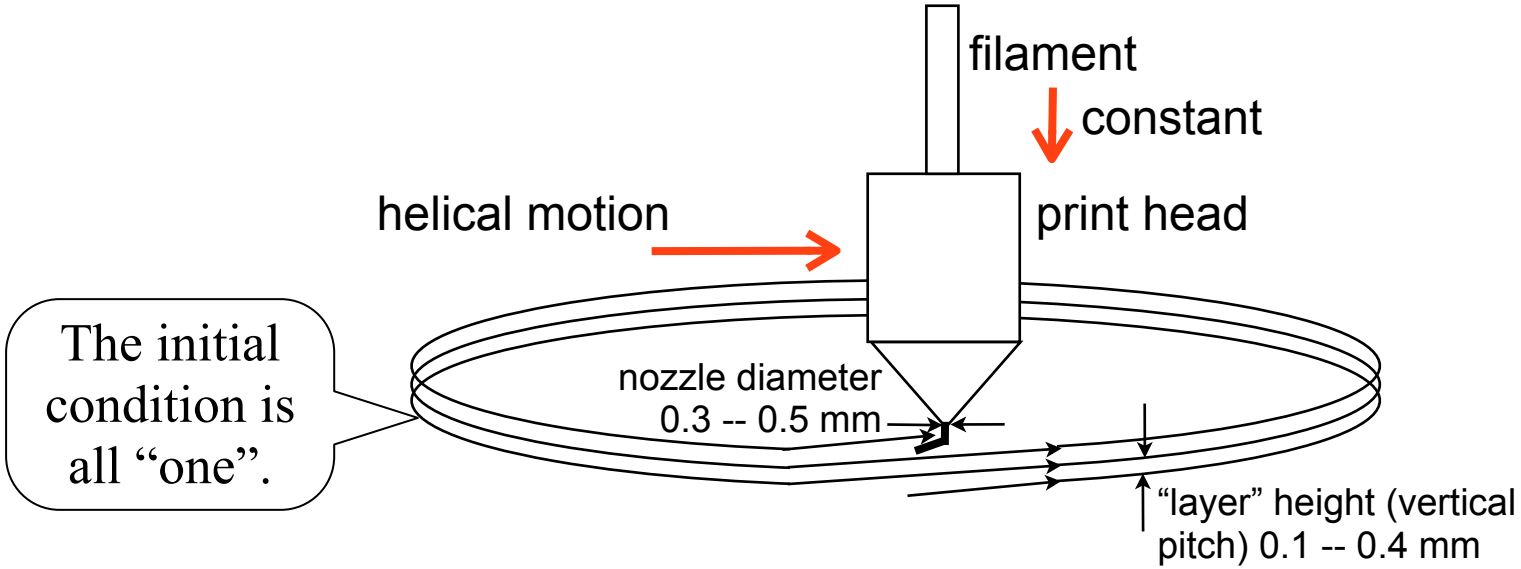


- **"FDM" 3D-printing can be interpreted as stochastic asynchronous CA** (cellular automata)**.**
  - A printing head generates 1D on/off patterns.
  - Fluctuated patterns are similar to patterns generated by stochastic CA.



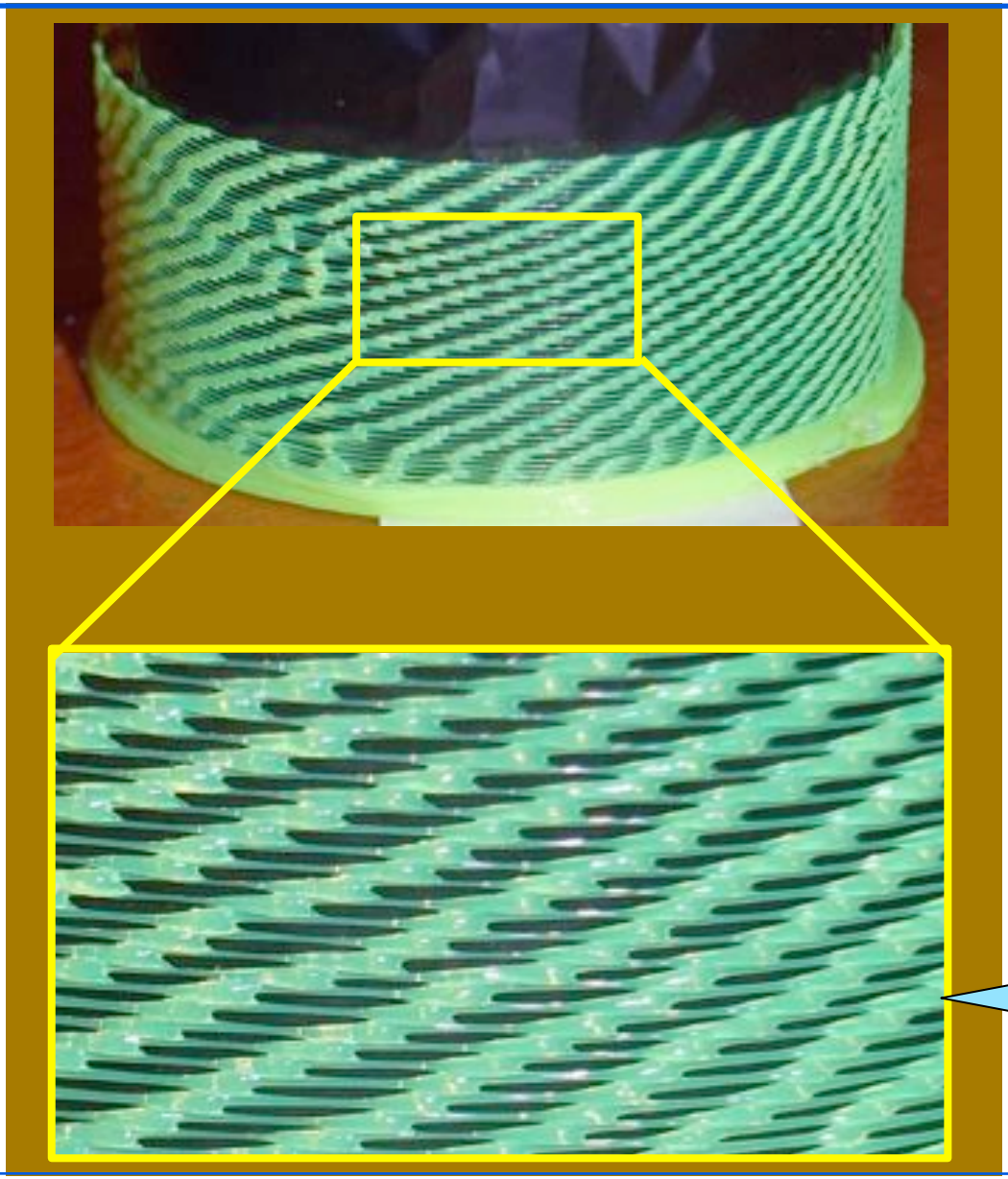
Proposal: Method for 1D CA-like pattern generation

- **Generates 1D CA-like patterns by a helical head motion.**



- **Is designed to generate artifacts as few as possible. (to generate pure self-organized patterns)**
  - Helical motion -- no layer transitions
  - Velocity of filament extrusion is constant and small.
  - Head speed is constant.
- **No 3D CAD/CAM program prints in this way!**

Typical printed patterns — Stripes

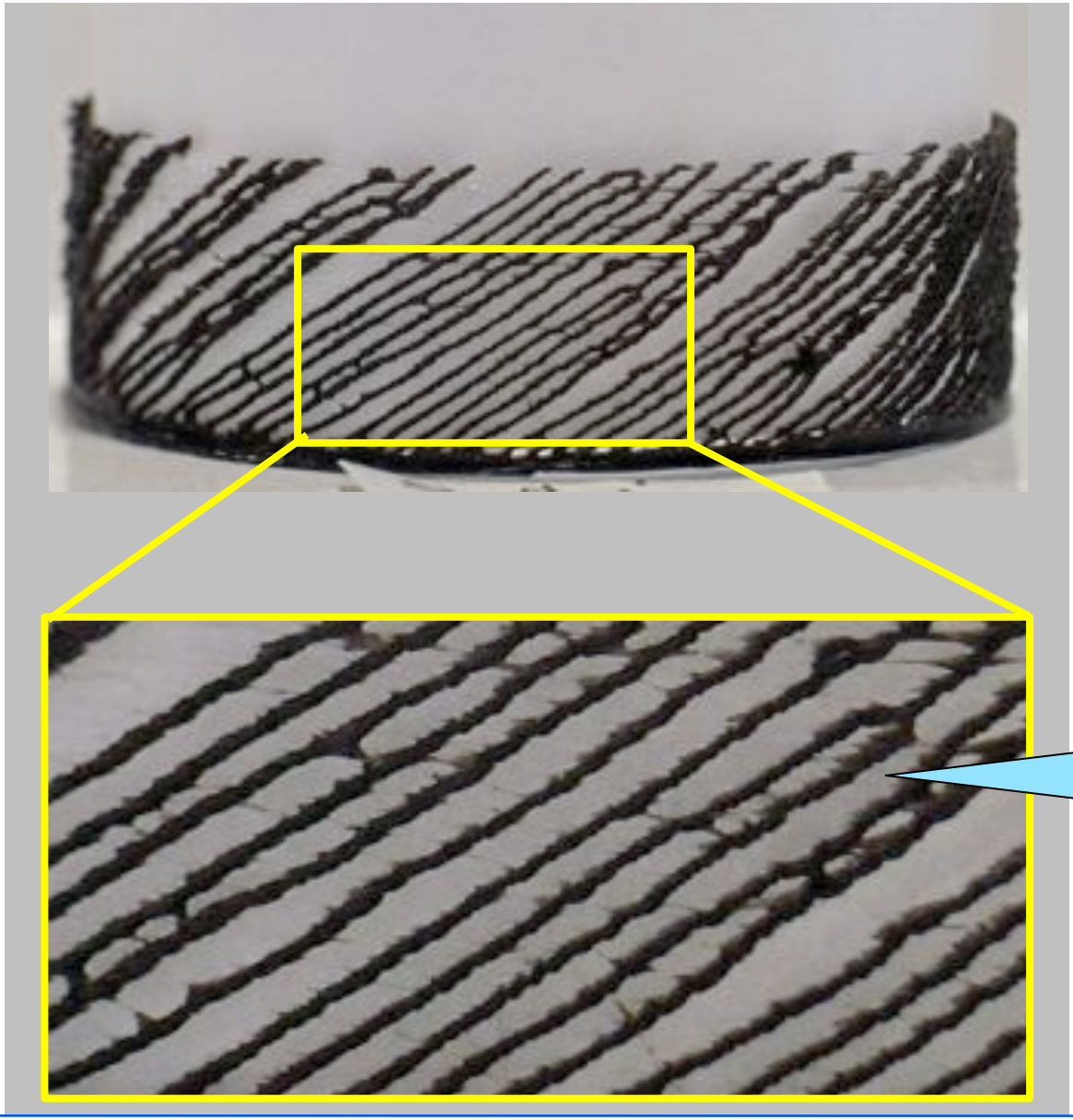


The layer is thick (0.3 mm).
The filament cross section is 0.045 mm^2.
PLA.

Stacked chunks and strings can be seen.

Mostly periodical and uniform pattern

Typical printed patterns — Stripes (cont'd)



The layer is thin (0.1 mm).
The filament cross section is 0.02 mm^2.
PLA.

Less uniform pattern
(Strings are torn)

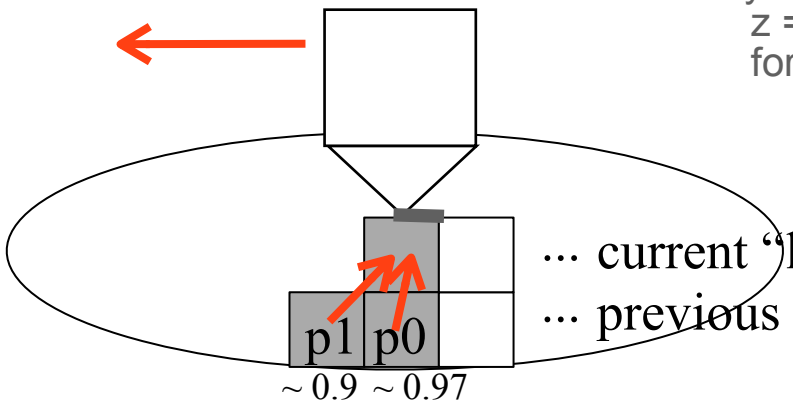
Printing process using Rostock MAX 3D printer

http://youtu.be/IJ15ysJR5l8

Basic computational model

- **A computational model that simulates printed 1D patterns (chunks only) was developed.**
  - **Explicit randomization** was (random numbers were) introduced instead of “natural randomization”.
  - A pattern grows by a probabilistic rule:

if extruded filament >= 1 /* certain amount */ then
  if cell[*l*–1][*i*] = 1 then cell[*l*][*i*] = 1 & filament cleared **at probability p0**
  else if cell[*l*–1][*i*+1] = 1 then cell[*l*][*i*] = 1 & filament cleared **at probability p1**
  else cell[*l*][*i*] = 0
else cell[*l*][*i*] = 0



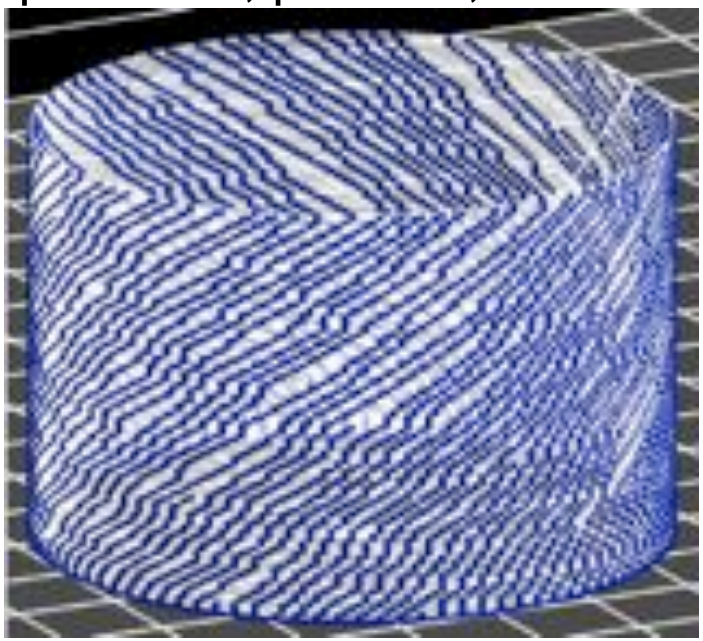

```
extrudedFilament = 0;
for layer in 1, 2, …, layers loop   // repeat for all layers
      z = 0.3 * layer;              // layer pitch is 0.3
      for i in 0, 1, …, 4 * 72 loop // repeat for all parts of a circle
            cell[layer][i] = 0;     // clear pattern
            if extrudedFilament >= 1 then
                  if cell[layer–1][i] > 0 and random() <= p0 or
                     cell[layer–1][i+1] > 0 and random() <= p1 then
                        cell[layer][i] = 1;              // fill the cell
                        extrudedFilament = 0.0;          // clear filament
            end if
            end if
            drawNextArc(cell[layer][i], z, i);
            extrusion = extrusion + e1; // extrude
      end loop
      cell[layer][steps] = cell[layer][0];
end loop
```

Only chunks are simulated.

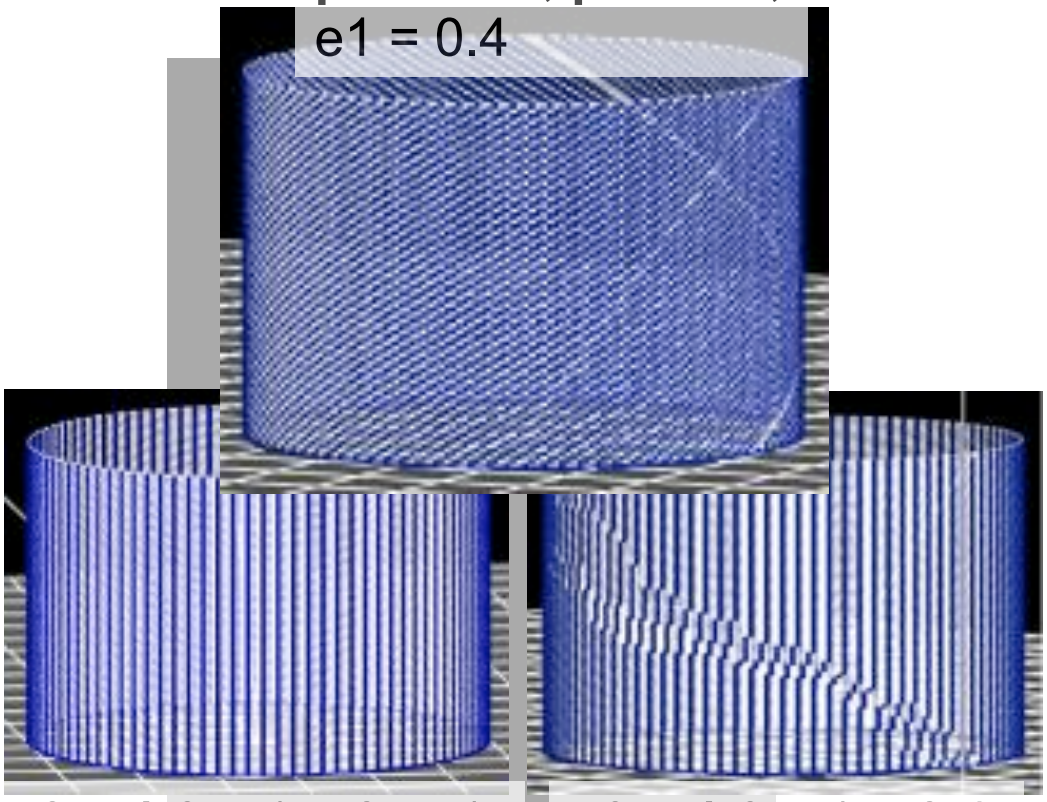
Simulation of typical patterns

- **A program written in Python generates G-code (CAM program) is used.**
  - G-code execution results are visualized by Repetier-Host (a CAM tool for 3D printers).

p0 = 0.99, p1 = 0.9, e1 = 0.4



p0 = 0.99, **p1 = 1.0**, e1 = 0.4



p0 = 1.0, p1 = 0 to 1, e1 = 0.4

p0 = 1.0, p1 = 0.4, e1 = 0.4

Various printed patterns and Simulation results

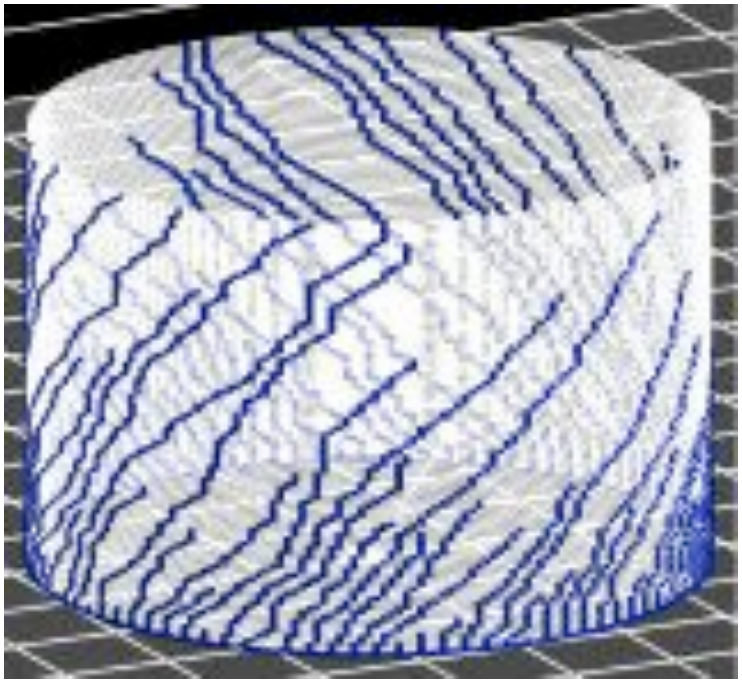
- Extinction of stripes
- Splitting and merging of stripes
- Waves and meshes

Extinction of stripes

A printed result

The layer height is 0.2 mm. PLA.

A simulation result

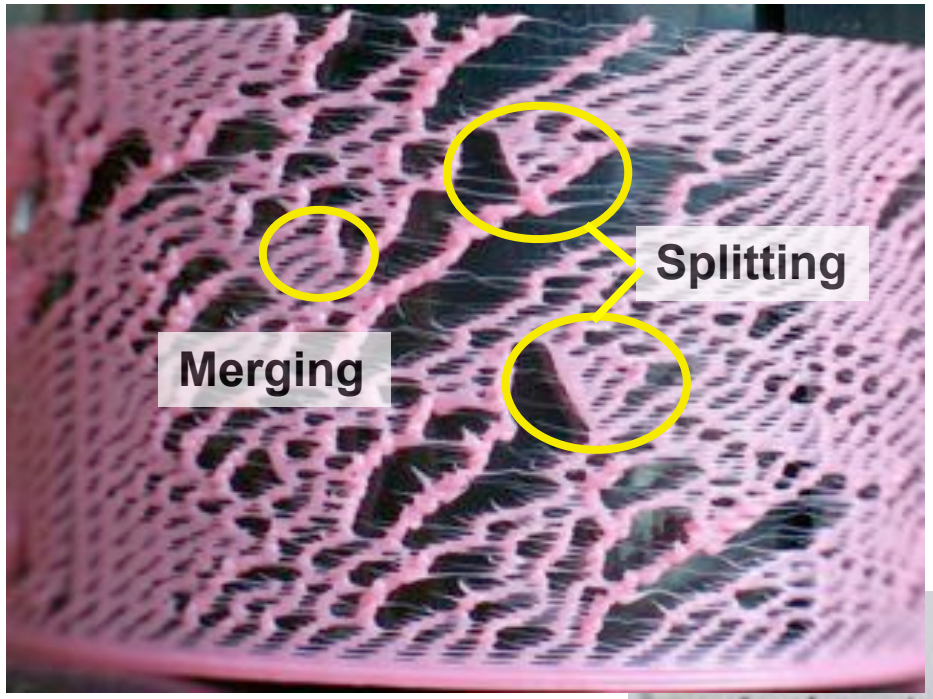


p1 = 0.9, **p0 = 0.97**, e1 = 0.6

Extinction of stripes (cont'd)

Splitting and merging stripes

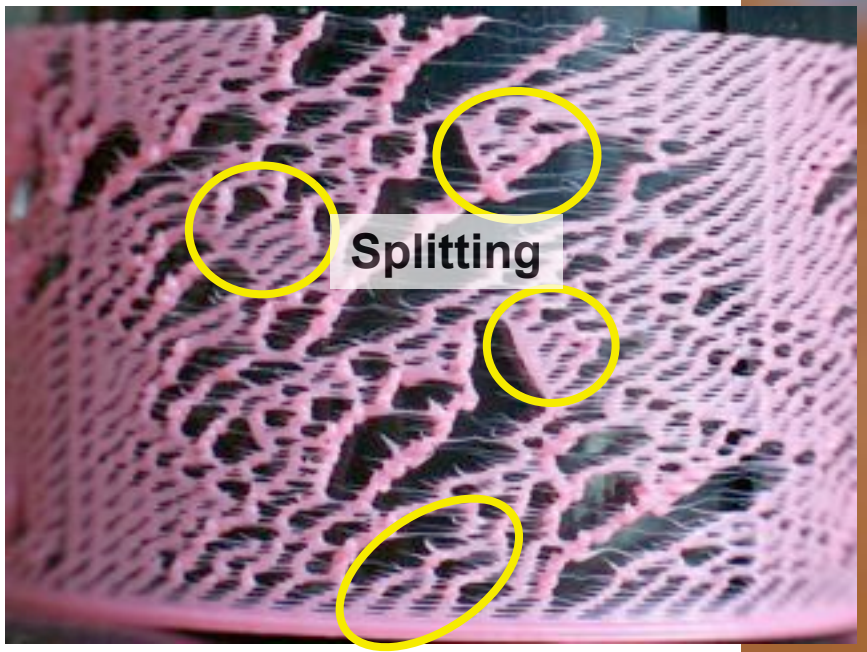
- **Printed results**

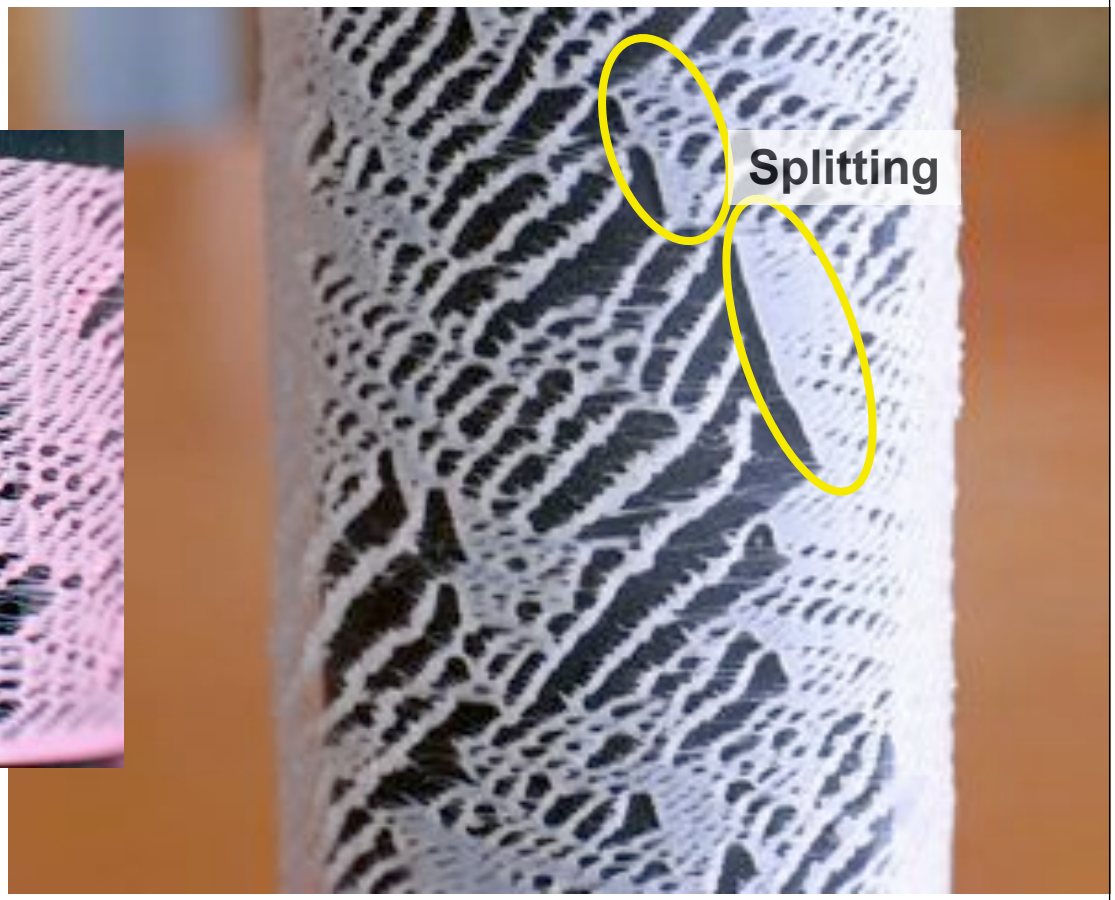


ABS

PLA

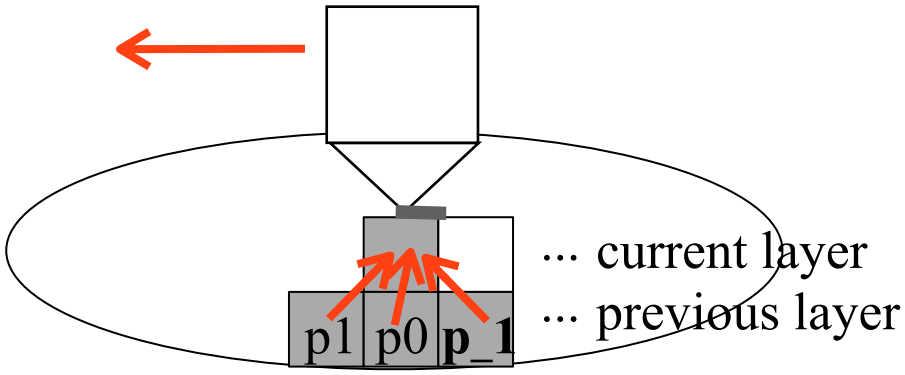
Splitting and merging stripes (cont'd)



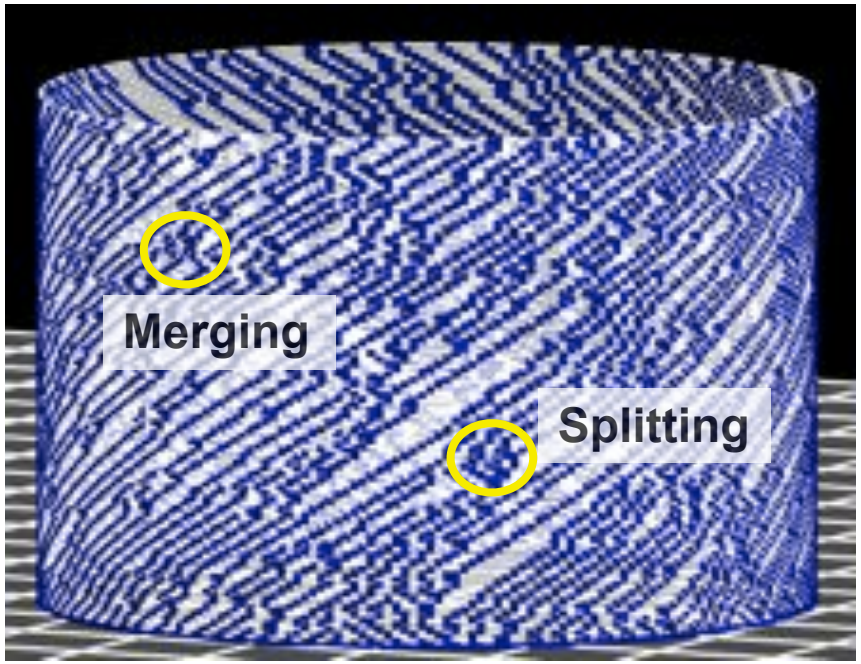


Computational model for splitting/merging stripes

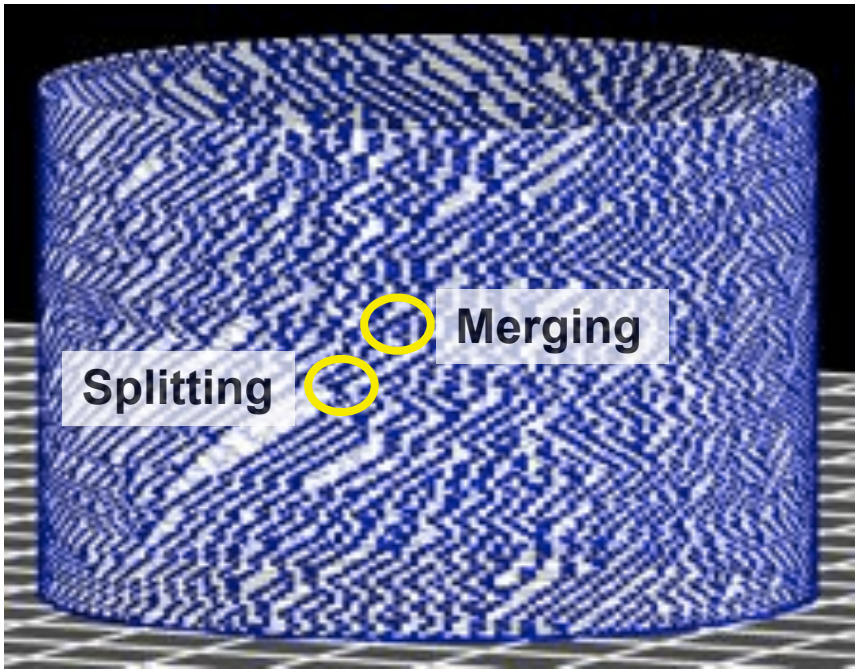
- **The computational rule must be extended to simulate splitting and merging.**
  - if extruded filament >= 1 then
    if cell[*l*–1][*i*–1] > 0 then cell[*l*][*i*] = 1 & filament cleared at probability p_1
    else if cell[*l*–1][*i*+1] > 0 then cell[*l*][*i*] = 1 & filament cleared at probability p1
    else if cell[*l*–1][*i*] = 1 then cell[*l*][*i*] = 1 & filament **reduced by C** /* C < 1 */ at probability p0
    else cell[*l*][*i*] = 0
  else cell[*l*][*i*] = 0



Simulation results of splitting/merging stripes



p_1 = 0.7, C = 0.8,
p1 = 0.9, p0 = 0.995, e1 = 0.4

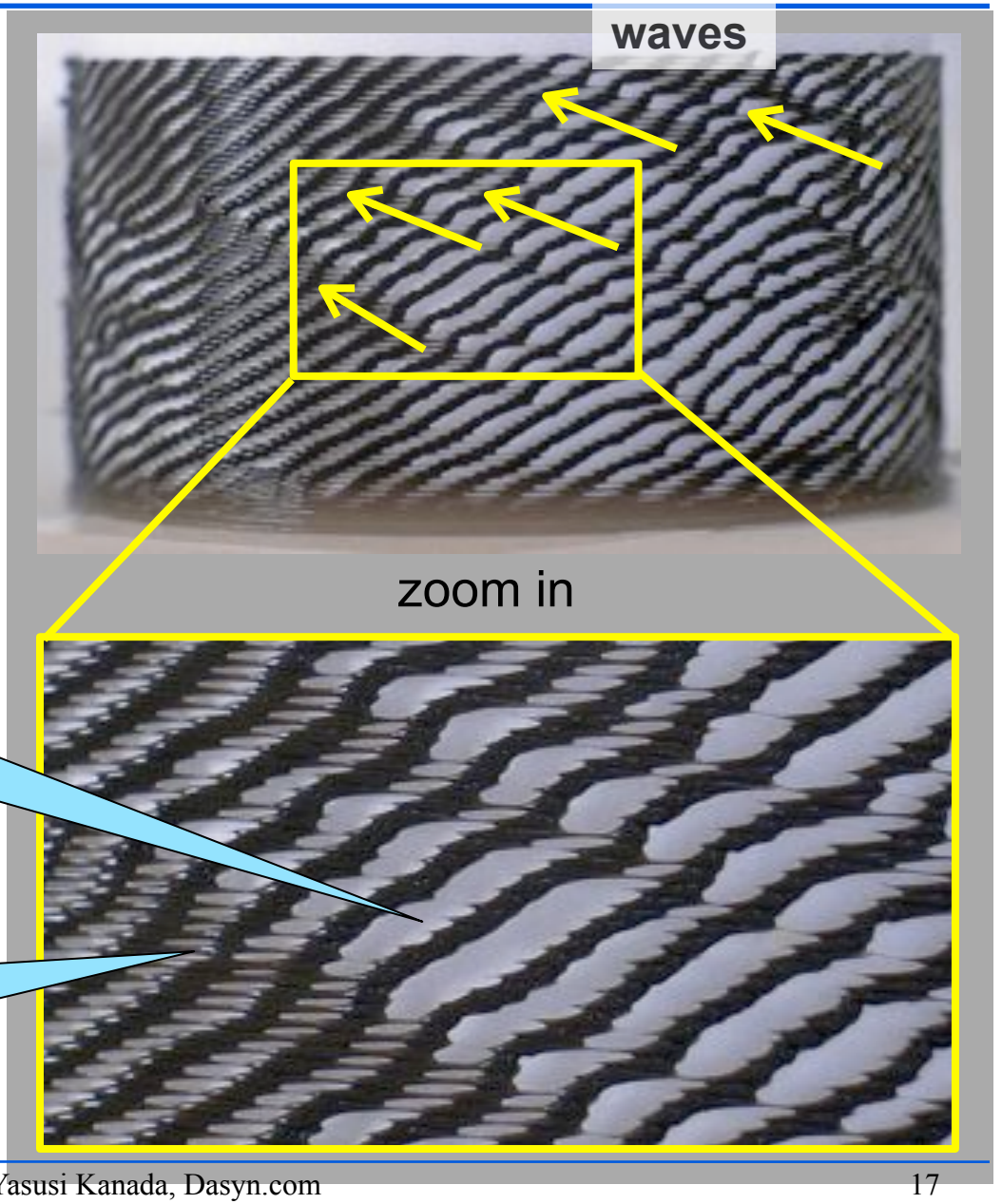


p_1 = 0.99, C = 0.9,
p1 = 0.9, p0 = 0.995, e1 = 0.4

Waves

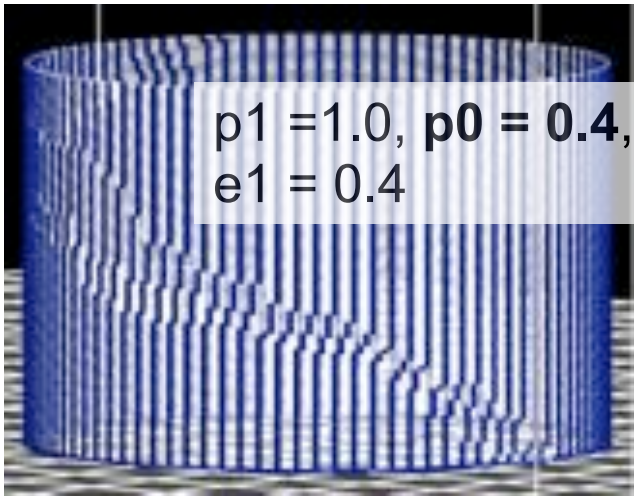
- **Stripes are weakly connected by thick strings.**
- **“Waves” moves across stripes.**

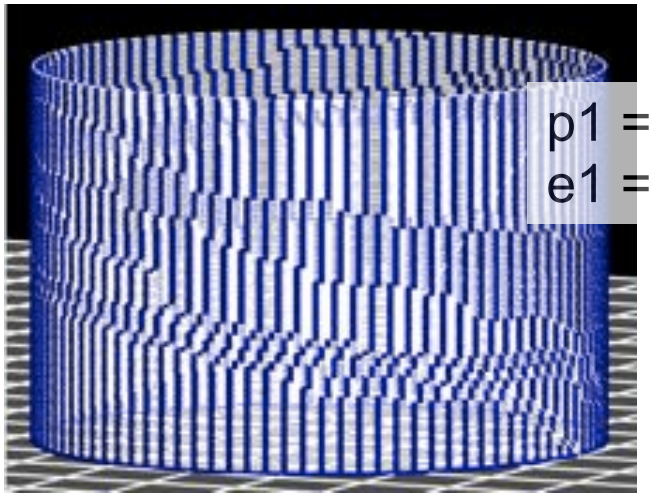
The layer height is 0.25 mm. PLA



Simulation of waves

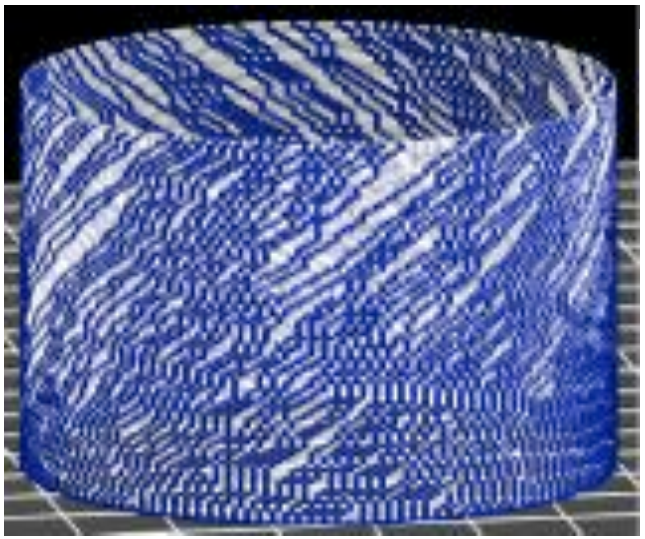
- **It is easy to see noises propagated across stripes.**





Noises are added to the initial condition.

- **It is less easy to see wave propagation here.**



p1 = 0.99, **p0 = 0.8**,
e1 = 0.5

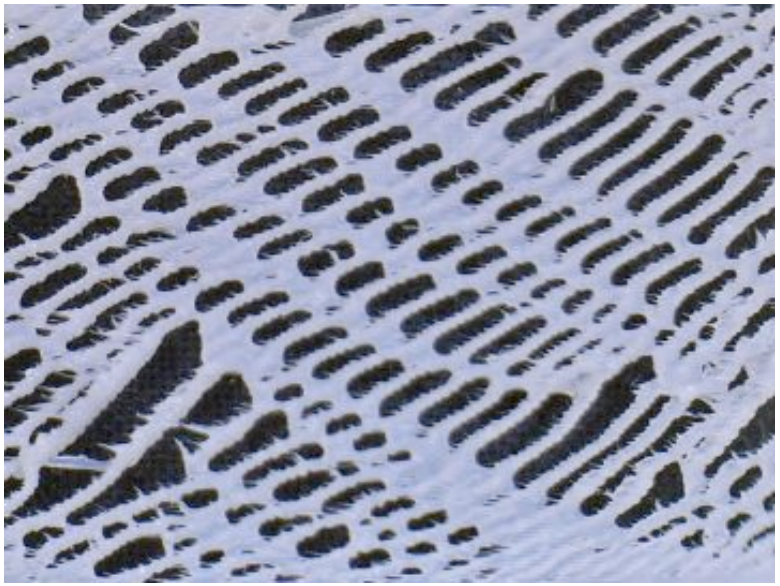
The observed waves and the simulated waves may be different because strings are not simulated.

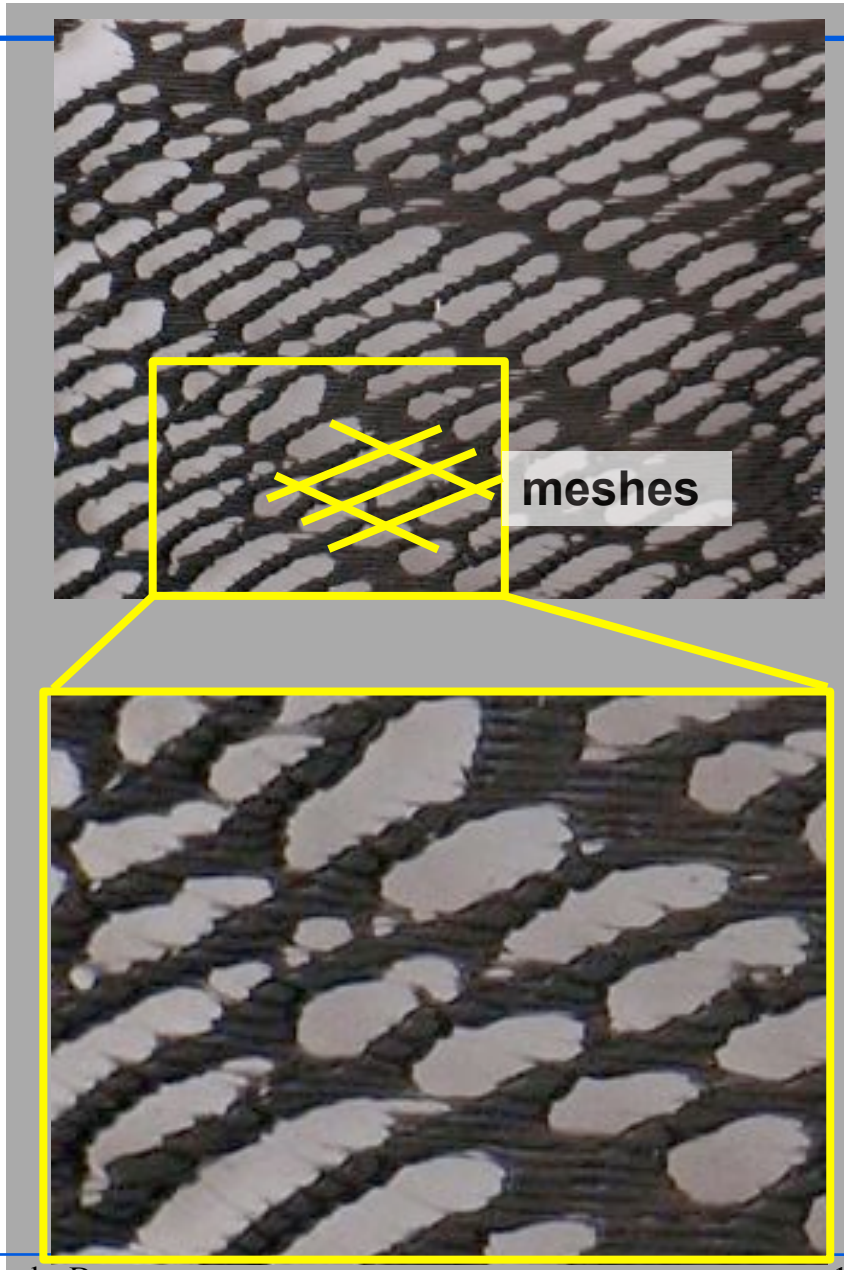
Meshes

- **Stripes are strongly connected.**
- **Meshes have not yet been successfully simulated.**

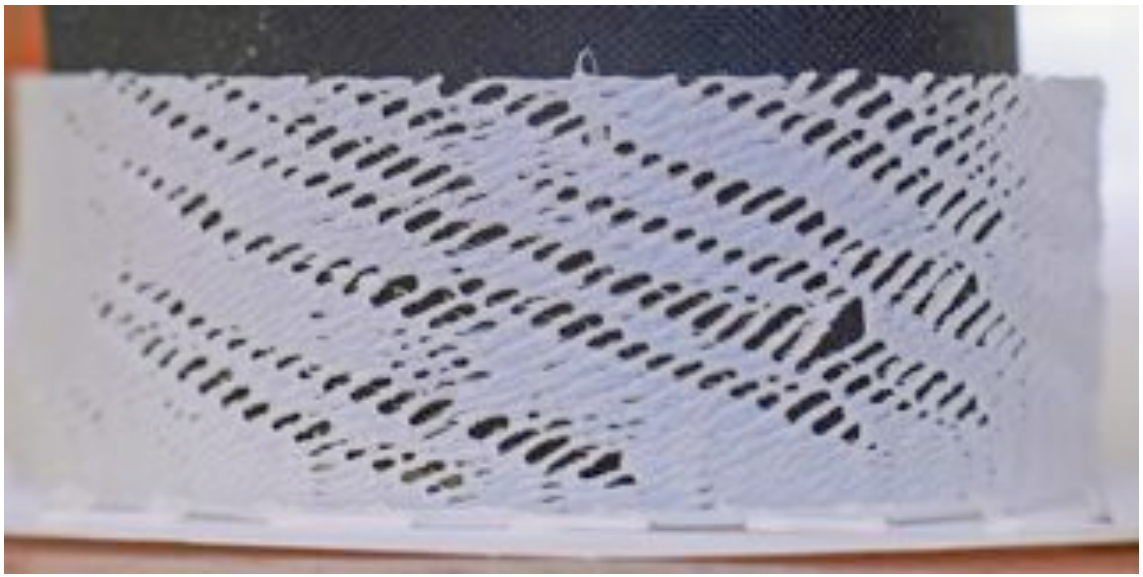
The layer height is 0.15 mm. PLA

ABS





Meshes (cont'd)



Summary

- **FDM 3D printers can generate stochastic self-organized patterns.**
  - “Pure” self-organized patterns can be generated by the 1D-CA-like printing method.
  - Fluctuating stripes, splitting and merging stripes, waves, and meshes can be generated.
- **The printed patterns can be (partially) simulated by 1D CA.**
  - Stripes can be simulated.
  - Splitting and merging stripes, waves, and meshes can be “simulated”, but it is not yet certain that it is the right way.