10th UCAAT User Conference on Advanced Automated Testing

ETSI The Standards People

Mutation Testing in Additive Manufacturing

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GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN IN PUBLICA COMMODA SEIT 1737

16/11/2023

Content

1) Additive Manufacturing
2) Mutation Testing in Additive Manufacturing
3) Feasibility Study: Gcode Mutation Operators
4) Lessons Learned
5) Conclusion

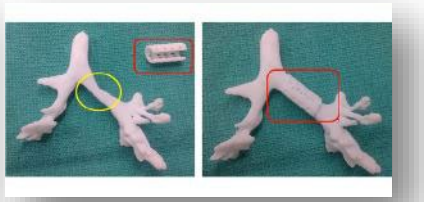
Additive Manufacturing (AM)

Foundations of 3D printing

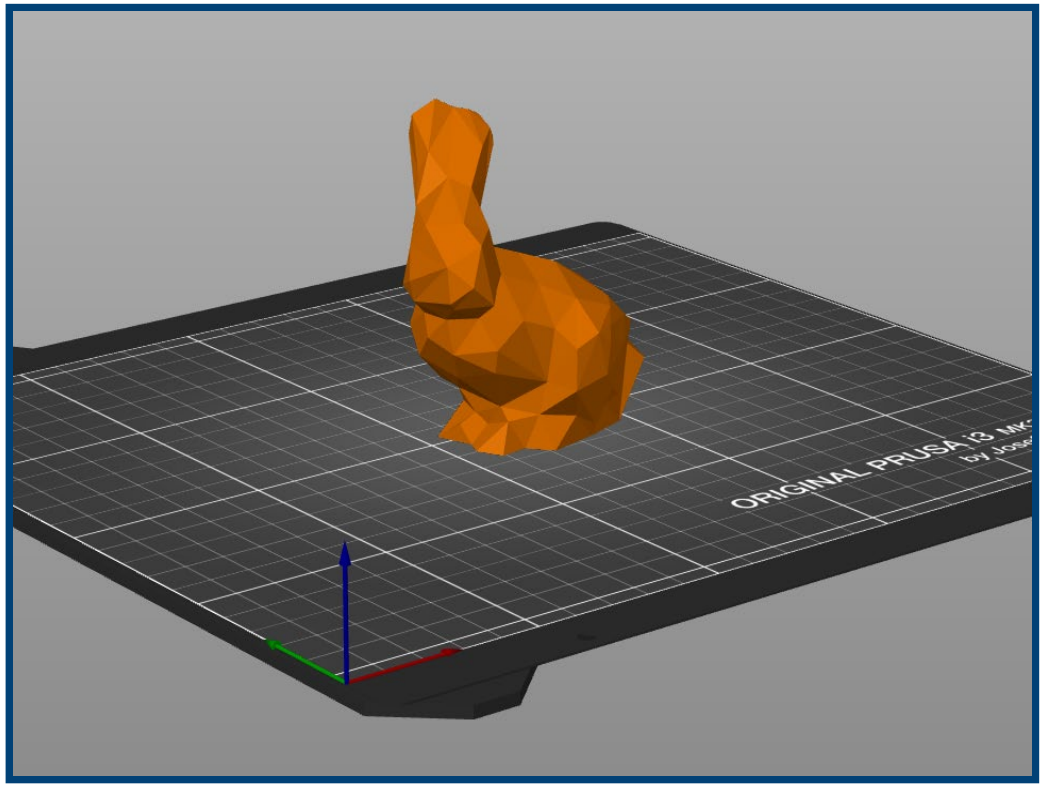
Layer-wise Fabrication

Hasbro, Toy Puzzle

AM Aircraft Hinge with
50% less weight (EADS)



Custom airway stent
(U. Michigan)

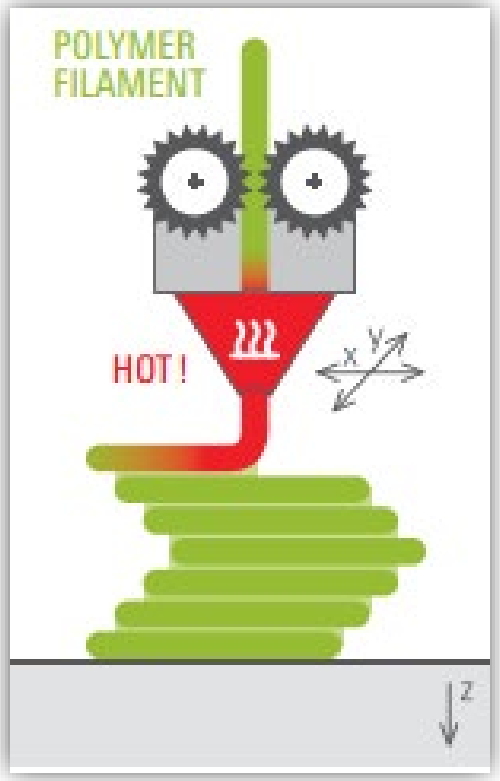


PrusaSlicer

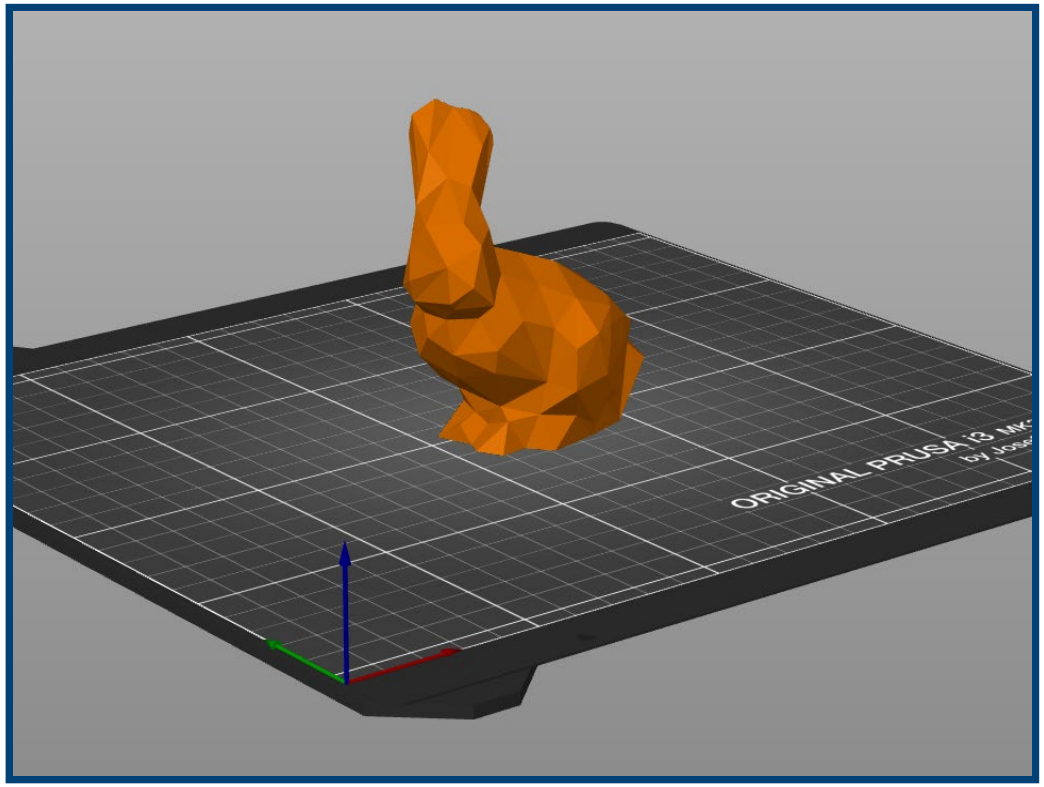
Additive Manufacturing (AM)

Foundations of 3D printing

Layer-wise Fabrication



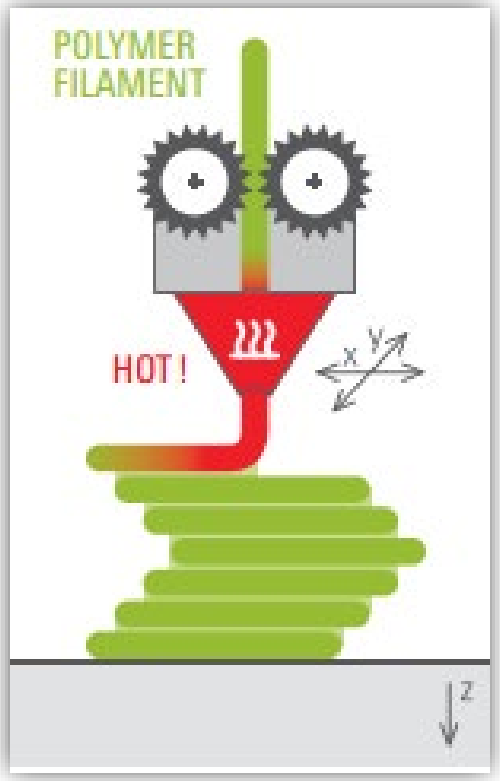
Formnext, AM Field Guide, Messe Frankfurt, 2021



Additive Manufacturing (AM)

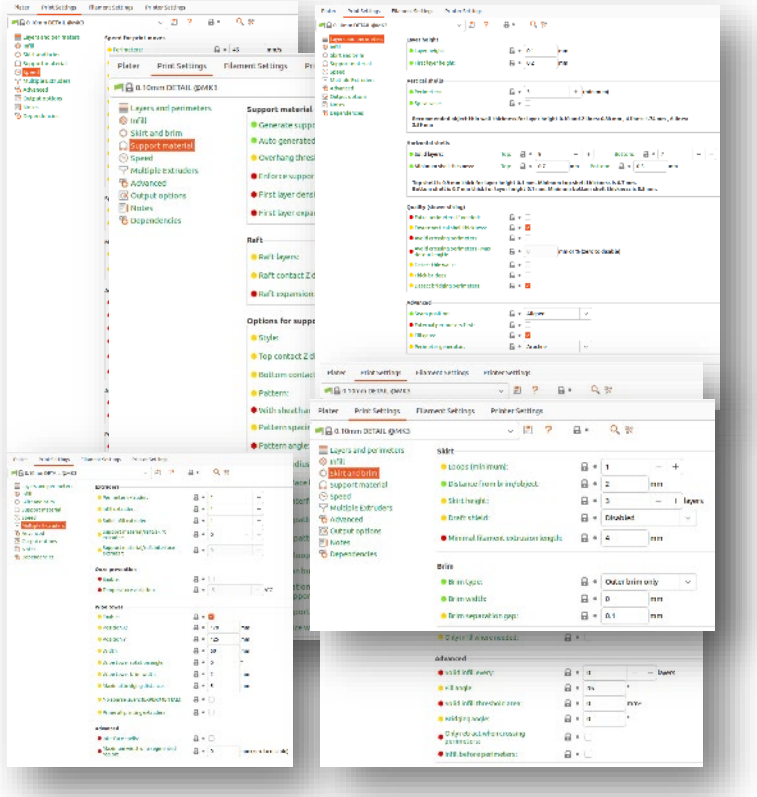
Difficulties in AM

Layer-wise Fabrication



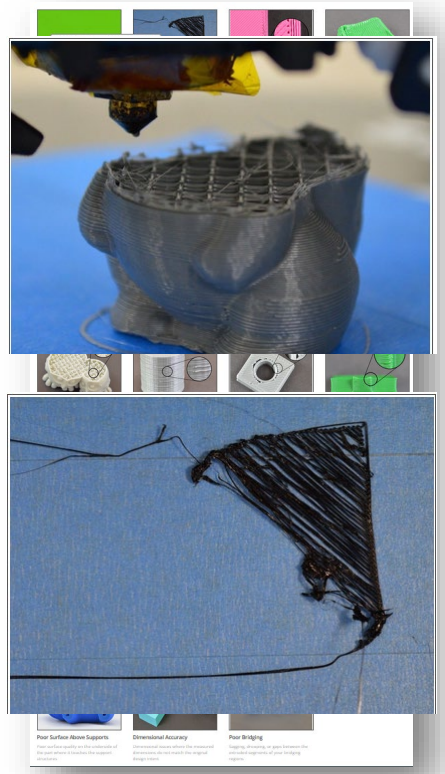
Formnext, AM Field Guide, Messe Frankfurt, 2021

Slicing and Instructions



PrusaSlicer

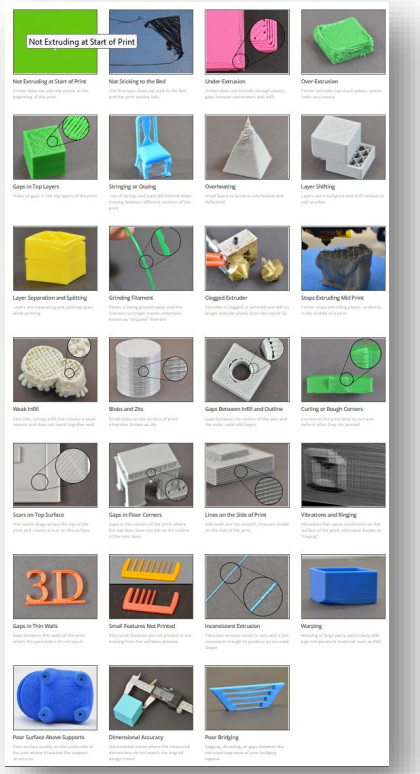
Huge Defect Variety



Simplify3D

Additive Manufacturing (AM)

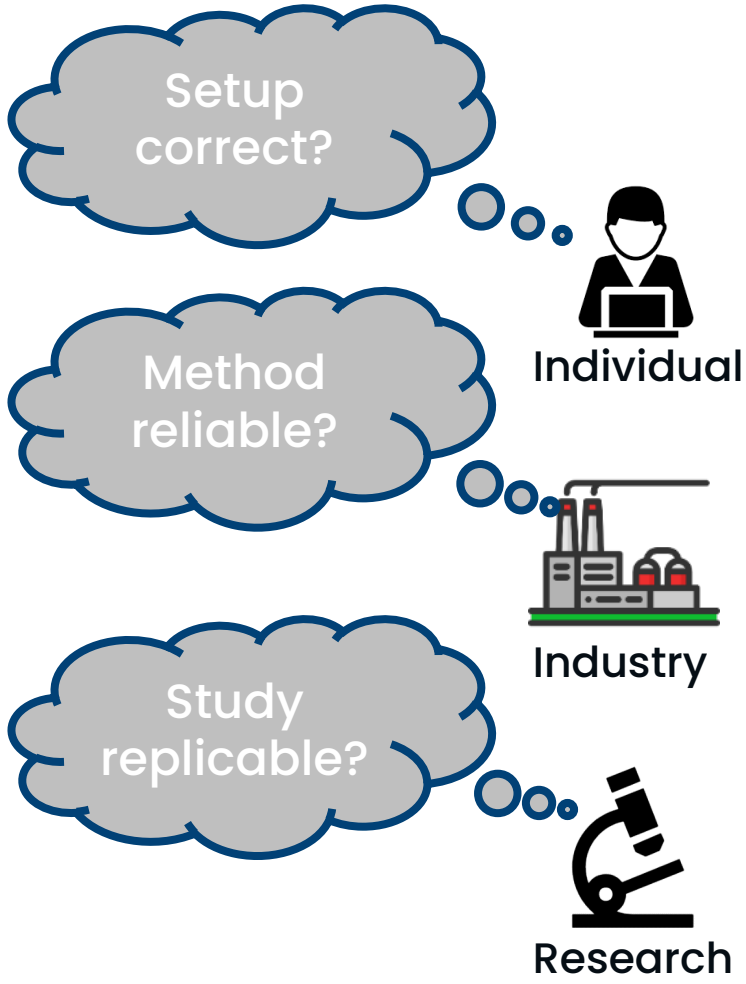
Huge Defect Variety



Simplify3D

Defect Detection Methods

Obico



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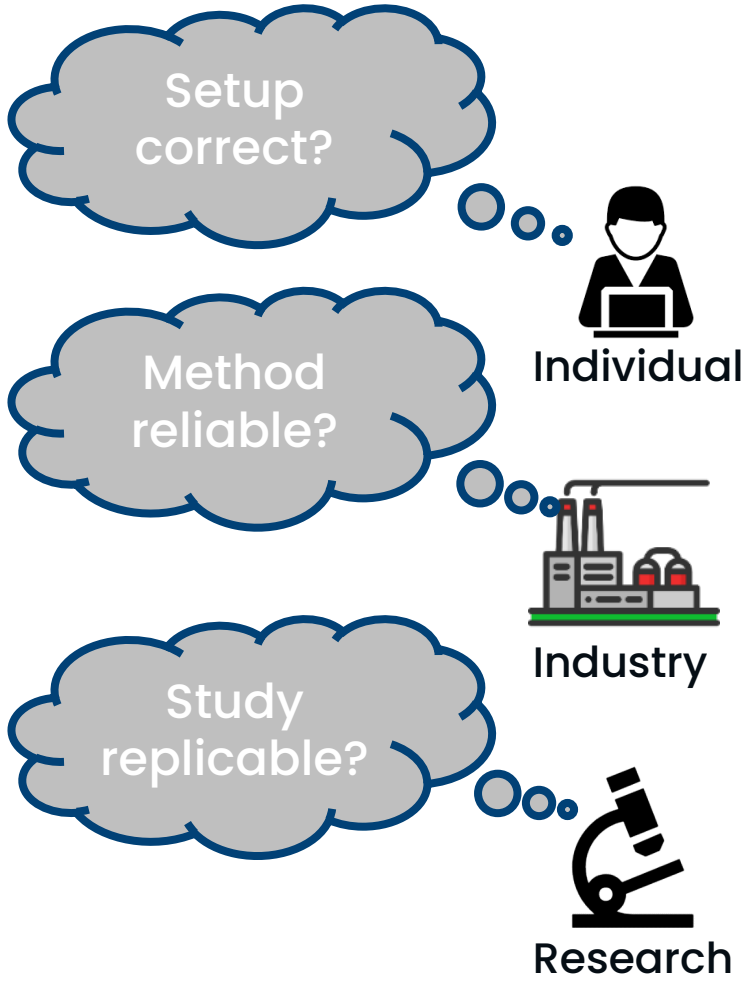
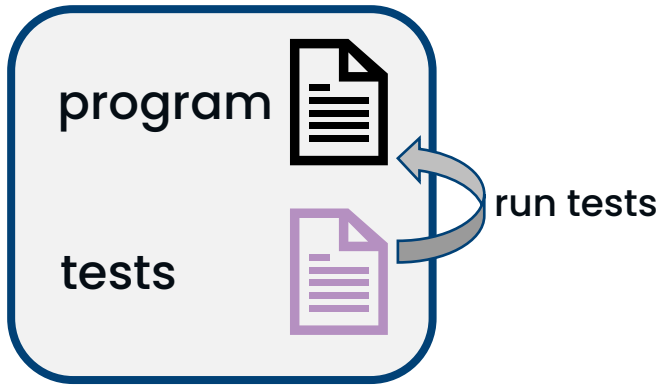
5) Conclusion



Mutation Testing in Software Engineering




```python
def bubbleSort(arr):
    n = len(arr)
    # optimize code, so if the array is already sorted, it doesn't need
    # to go through the entire process
    swapped = False
    # Traverse through all array elements
    for i in range(n-1):
        # range(n) also work but outer loop will
        # repeat one time more than needed.
        # Last i elements are already in place
        for j in range(0, n-i-1):

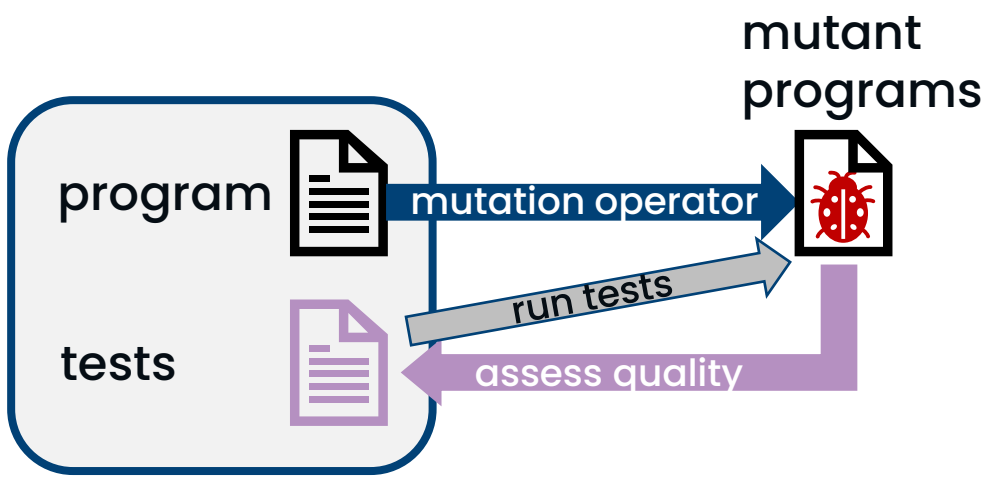
            # traverse the array from 0 to n-i-1
            # Swap if the element found is greater
            # than the next element
            if arr[j] > arr[j + 1]:
                swapped = True
                arr[j], arr[j + 1] = arr[j + 1], arr[j]

        if not swapped:
            # if we haven't needed to make a single swap, we
            # can just exit the main loop.
            return
```

program

Bubblesort, geeksforgeeks

Mutation Testing in Software Engineering



To what extent can my tests find bugs in my source code?

Adapted from Petrovic et al., 2021

```
def bubbleSort(arr):
    n = len(arr)
    # optimize code, so if the array is already sorted, it doesn't need
    # to go through the entire process
    swapped = False
    # Traverse through all array elements
    for i in range(n+1):
        # range(n) also work but outer loop will
        # repeat one time more than needed.
        # Last i elements are already in place
        for j in range(0, n-i-1):

            # traverse the array from 0 to n-i-1
            # Swap if the element found is greater
            # than the next element
            if arr[j] > arr[j + 1]:
                swapped = True
                arr[j], arr[j + 1] = arr[j + 1], arr[j]

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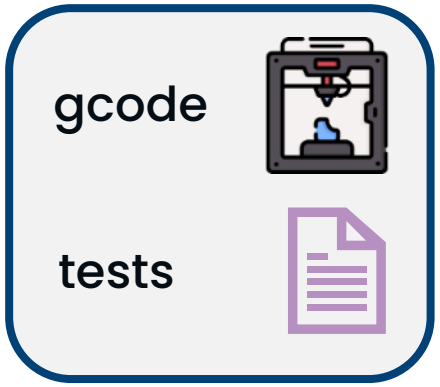
```

mutation operator

mutant program

Bubblesort, geeksforgeeks

Mutation Testing in AM



- One Instruction per Line
  - Comments
  - Movement
    - Feedrate (Speed)
    - Coordinates
    - Filament Extrusion
  - Misc
    - Temperature
    - Fan
    - Progress

```
;TYPE:External perimeter
G1 F1200
G1 X81.41 Y81.41 E.53867
G1 X98.59 Y81.41 E.53867
G1 X98.59 Y98.59 E.53867
G1 X81.47 Y98.59 E.53678
M204 P1000
G1 X81.514 Y98.204 F9000
G1 E-2.24 F2700
;WIPE_START
G1 F7200
G1 X81.461 Y96.03 E-.912
;WIPE_END
G1 E-.048 F2700
G1 Z.4 F720
```

object perimeter

gcode

3D printer images from: www.freepik.com

Mutation Testing in AM

gcode 

tests 

- One Instruction per Line
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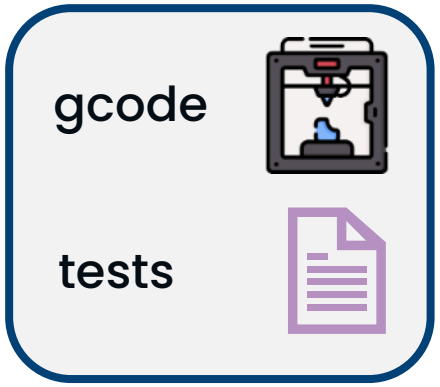
G1 X81.461 Y96.03 E-.912
;WIPE_END
G1 E-.048 F2700
G1 Z.4 F720
```

gcode

object perimeter

1200 mm/s

Mutation Testing in AM



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G1 Z.4 F720
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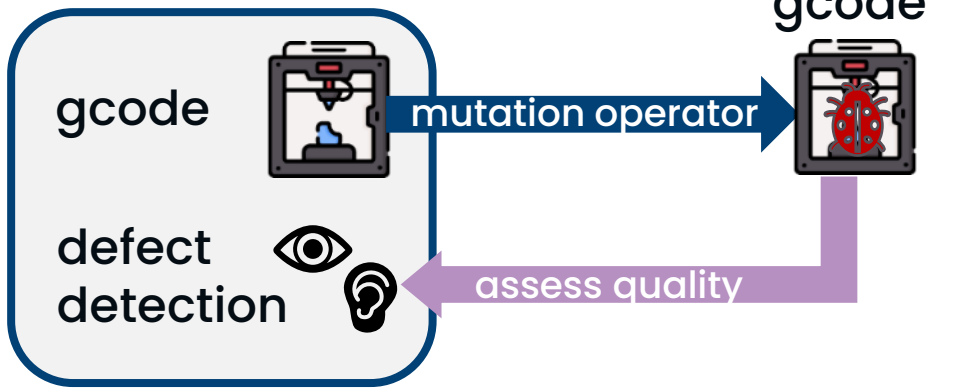
object perimeter

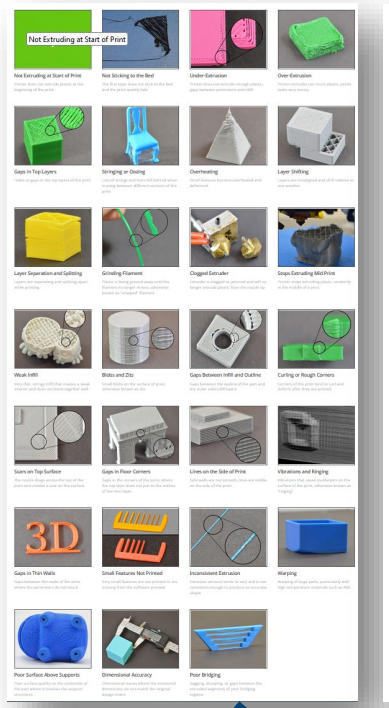
1200 mm/s

gcode

Mutation Testing in AM



To what extent can mutation operators imitate print defects to evaluate defect detection methods?




```
;TYPE:External perimeter
G1 F1200
G1 X81.41 Y81.41 E.53867
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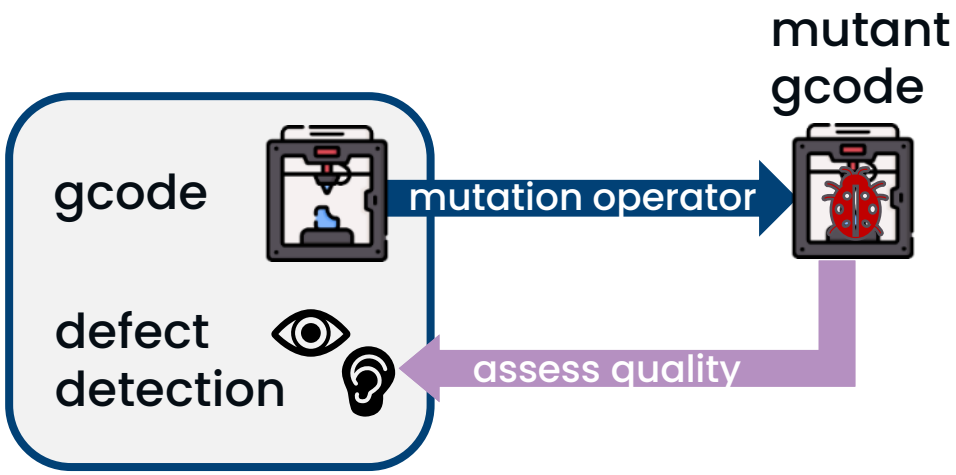
```

object perimeter

1200 mm/s

gcode

Mutation Testing in AM



Control severity

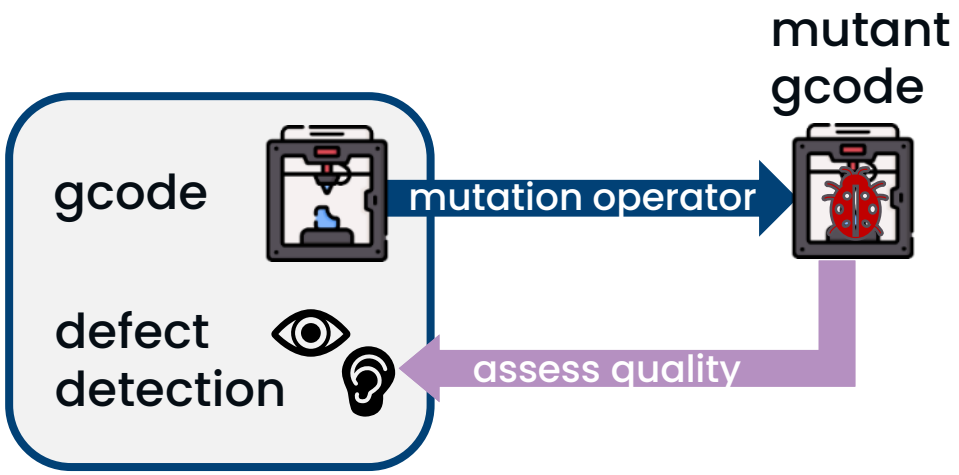
- Instruction Wise

```
;TYPE:External perimeter
G1 F10000
G1 X81     Y81.41 E.53867
G1 X98.59 Y81     E.53867
G1 X98.59 Y98.59 E0
G1 X81.47 Y98.59 E.53678
M204 P1000
G1 X81.514 Y98.204 F9000
G1 E-2.24 F2700
;WIPE_START
G1 F7200
G1 X81.461 Y96.03 E-.912
;WIPE_END
G1 E-.048 F2700
G1 Z.4 F720
```

mutation operator

mutant gcode

Mutation Testing in AM



Control severity

- Instruction Wise
- Feature Wise

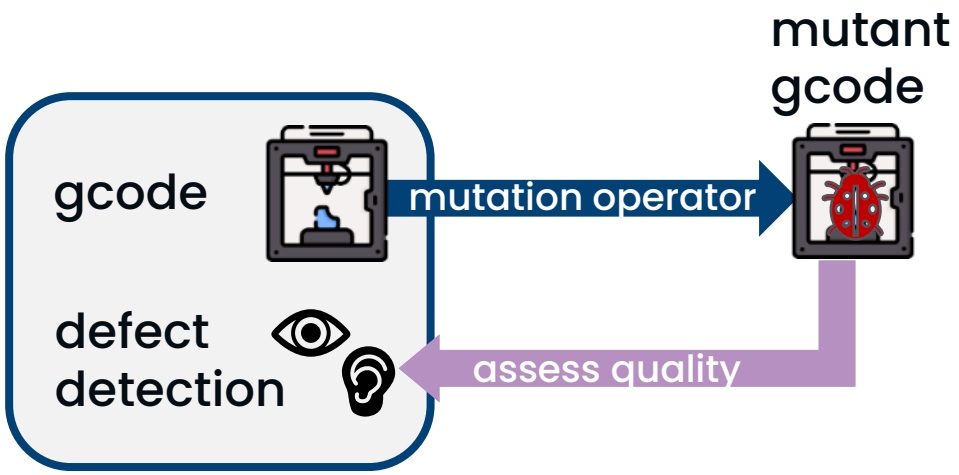
```
;TYPE:External perimeter
G1 F1200
G1 X81.41 Y81.41 E2
G1 X98.59 Y81.41 E0.3
G1 X98.59 Y98.59 E0.3
G1 X81.47 Y98.59 E2
M204 P1000
G1 X81.514 Y98.204 F9000
G1 E-2.24 F2700
;WIPE_START
G1 F7200
G1 X81.461 Y96.03 E-.912
;WIPE_END
G1 E-.048 F2700
G1 Z.4 F720
```

mutation operator

1200 mm/s

mutant gcode

Mutation Testing in AM



Control severity

- Instruction Wise
- Feature Wise
- Layer Wise

```
;TYPE:External perimeter
G1 F1200
G1 X81.41 Y81.41 E0
G1 X98.59 Y81.41 E0
G1 X98.59 Y98.59 E0
G1 X81.47 Y98.59 E0
M204 P1000
G1 X81.514 Y98.204 F9000
G1 E-2.24 F2700
;WIPE_START
G1 F7200
G1 X81.461 Y96.03 E0
;WIPE_END
G1 E0      F2700
G1 Z.4 F720
```

mutation operator

1200 mm/s

mutant gcode

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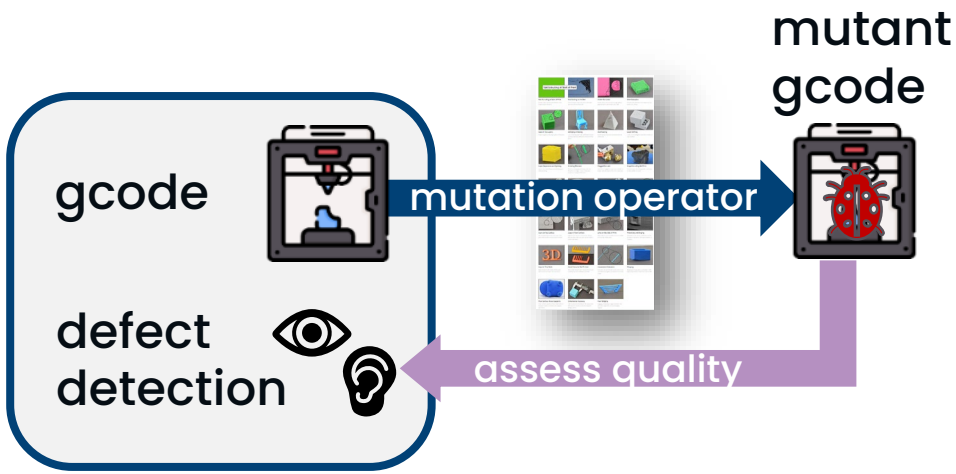
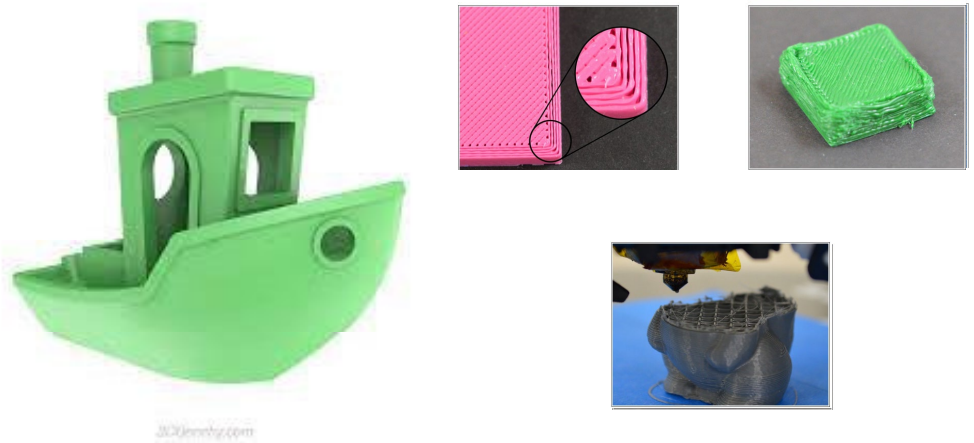




Under Extrusion

Under Extrusion

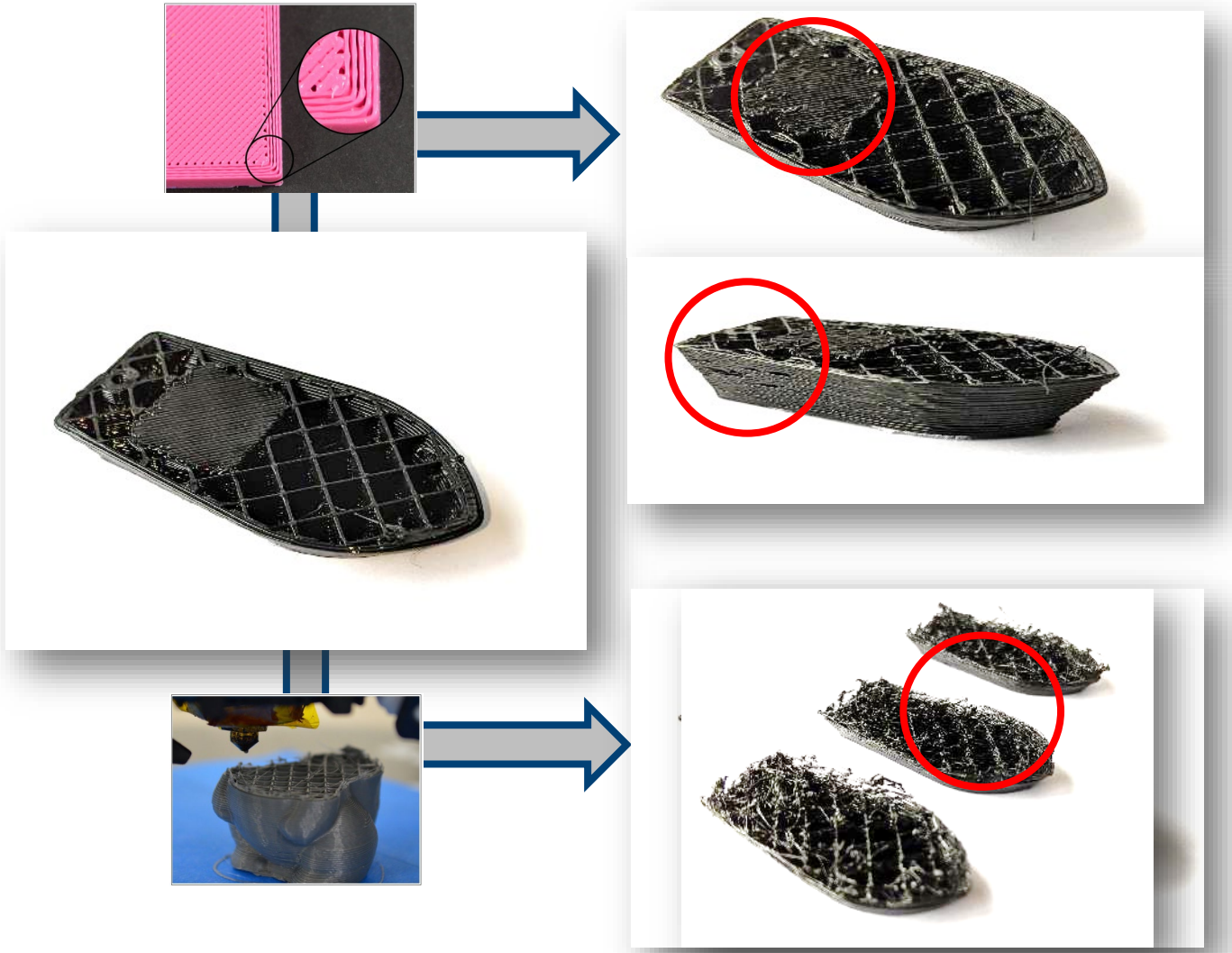
- Printer extrudes less plastic

Reason

- Clogged Nozzle
- Wrong slicer configuration

Approach

- Mutate extrusion parameter
  1. Constant layerwise reduction
  2. Increasing reduction layerwise

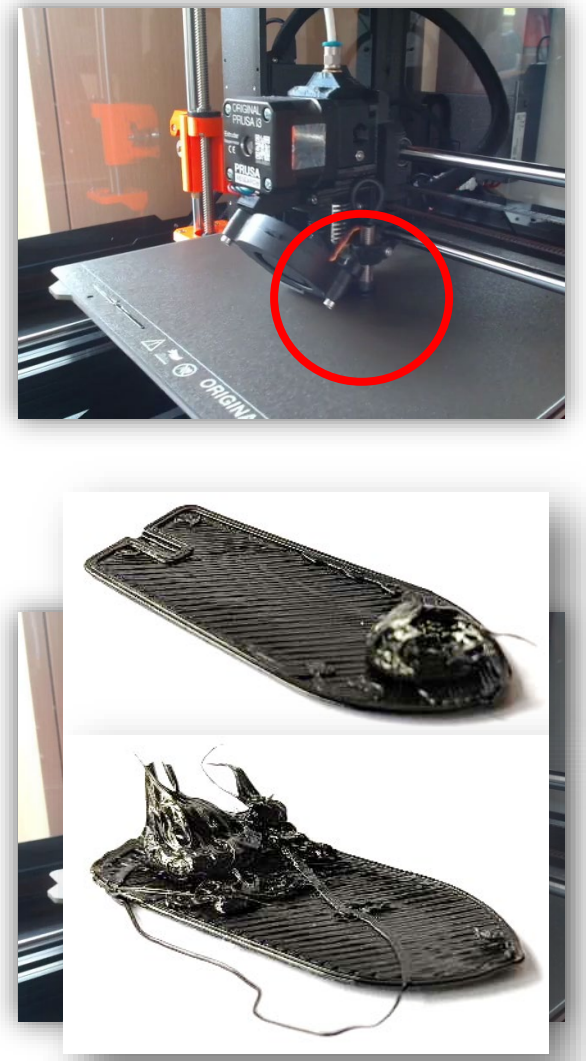


Not Sticking to Bed

Not Sticking to Bed
- Print does not stick
- Quickly fails

Reason
- Dirty print bed
- Speed to high
- Temperature issues
- Nozzle to high

Approach
- Mutate speed, temperature, height
- Start with layer 2



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Lessons Learned

- Real problems reproducible by gcode mutants
  - Depending on operator near same results
- Mutations are time consuming
  - First-layer quicker than mid-layer
- First-layer rather severe defects
  - Leave first two layers intact
- Defect masking
  - Small deviations quickly lead to larger faults

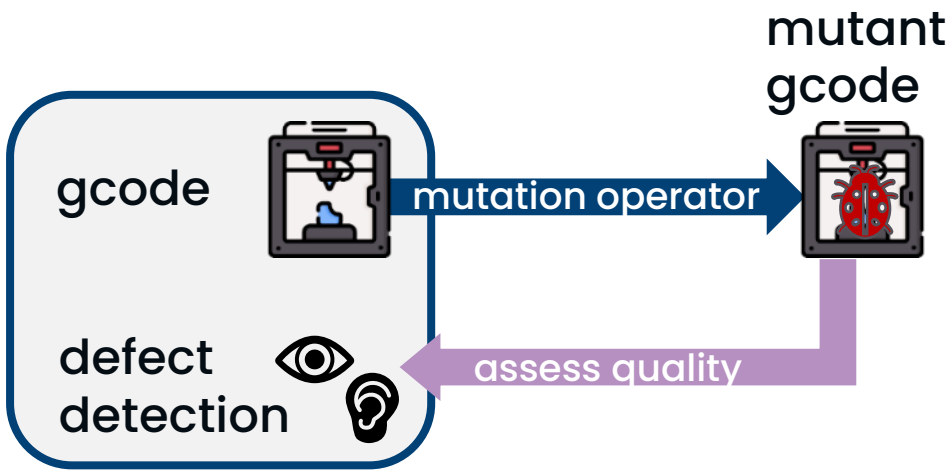
Conclusion

Mutation operators

- Can be applied to gcode
- Can partially imitate print defects
- May serve as benchmark for defect detection
- Non intrusive and repeatable

Future work

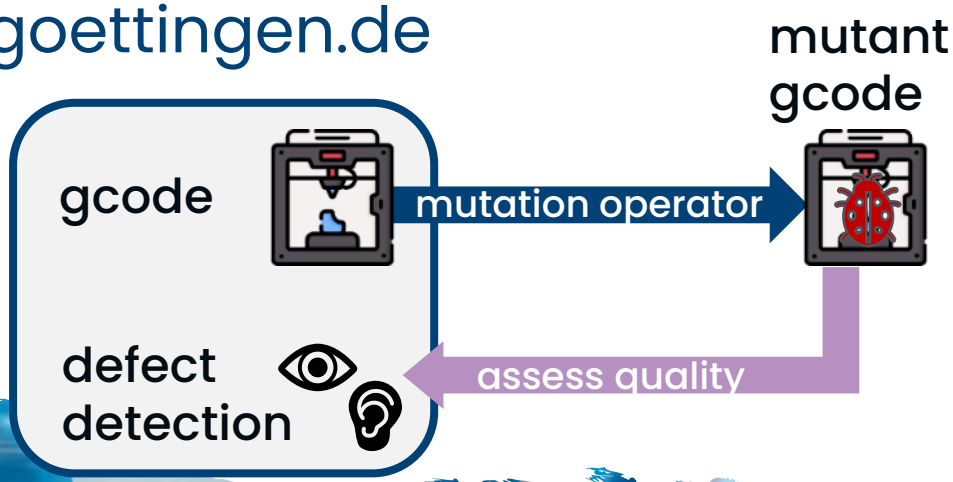
1. Quantitative evaluation
   - Different prints
   - Different printers
   - Comprehensive mutant mapping
2. Further analysis
   - Mutant injection points
   - Mutant dependencies



To what extent can mutation operators imitate print defects to evaluate defect detection methods?

Thank you for your attention!

Contact me:
johannes.erbel@cs.uni-goettingen.de



Backup

Warping

Warping
- Curled corners
- High temperature prints

Reason
- Plastic shrinks when cooled

Approach
- Layer injection
- Repeat perimeter movement
- Turn on fan
- Turn heatbed off