Chapter 4: Additive Manufacturing

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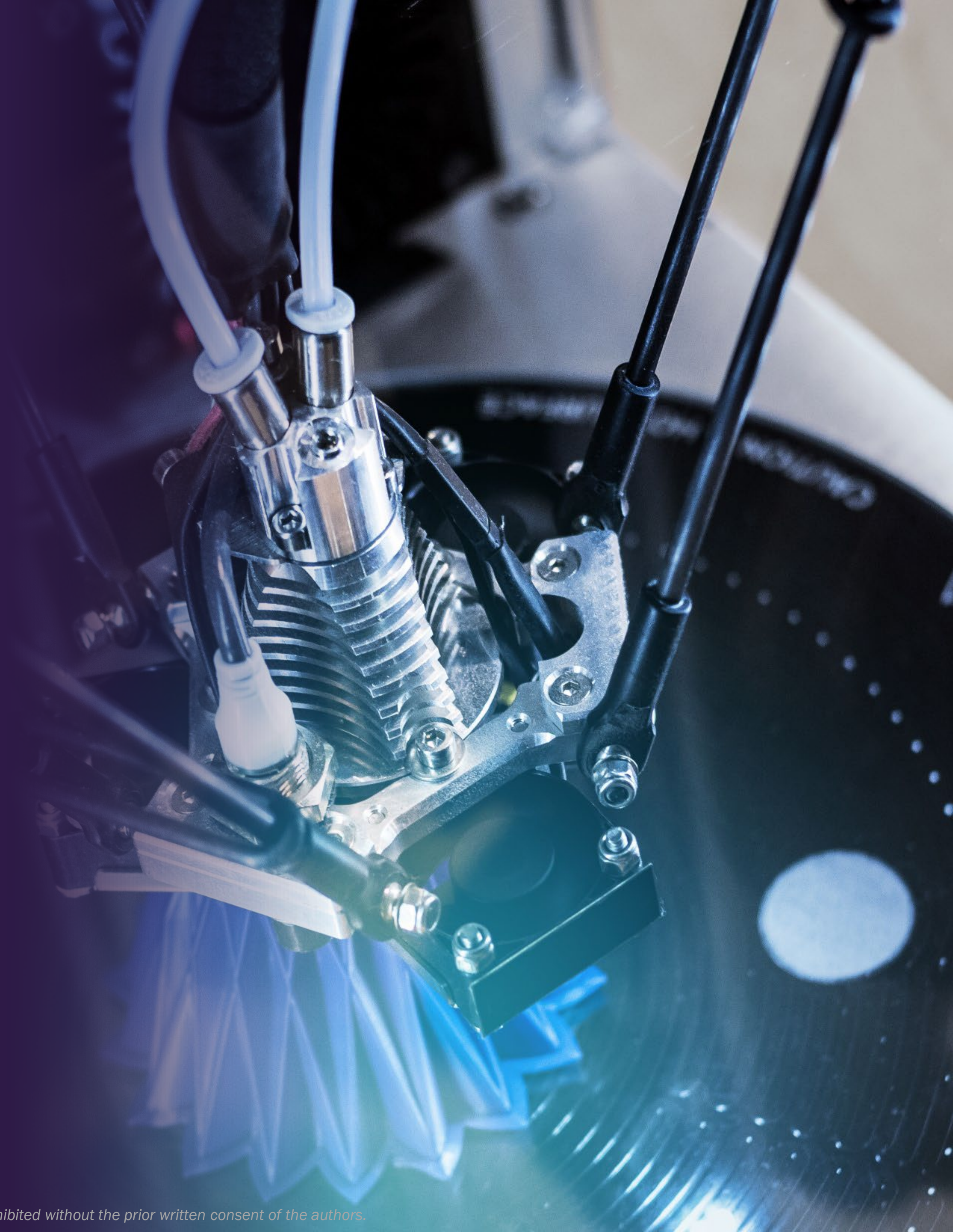

Outline

Additive Manufacturing

Chapter 4

Chapter 8

- Additive manufacturing represents processes where we transform the part from Form A (most of the time 'nothing') to Form B by addition of material.

- The fundamental concept is that we augment the volume of materials throughout the process.

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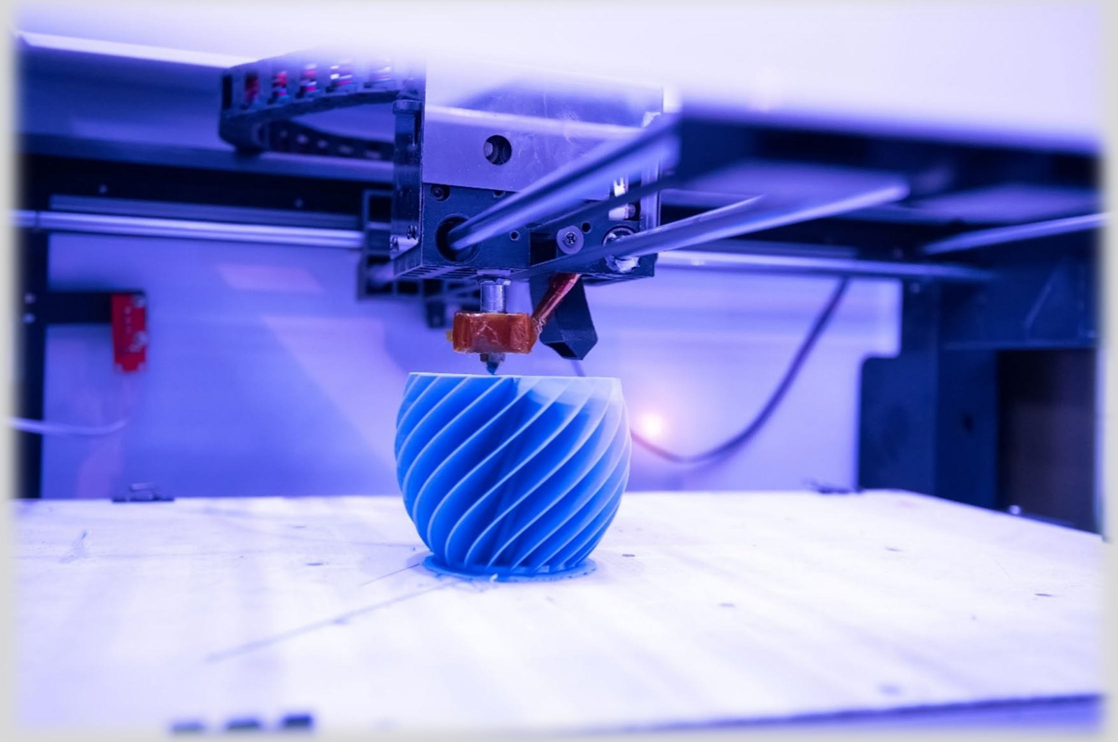
- Composite manufacturing, 3D Printing, SLS, SLA, FFF are examples of Additive Manufacturing processes.

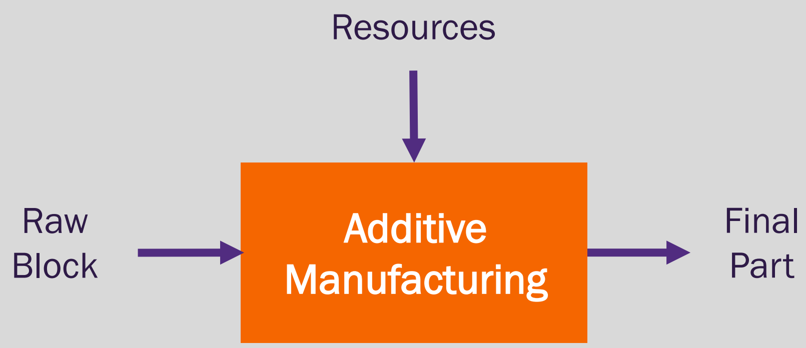


Additive Manufacturing

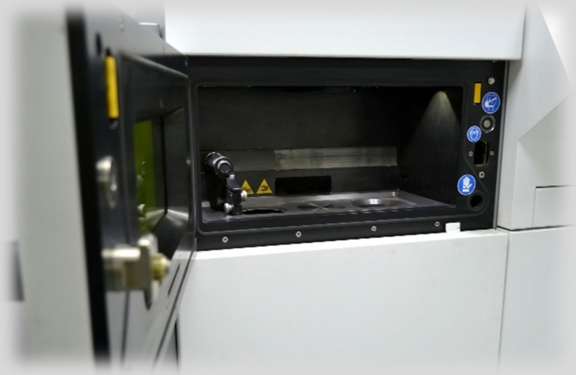
- Additive manufacturing uses materials, machinery and tools to build up material layers or zones gradually creating the final part.

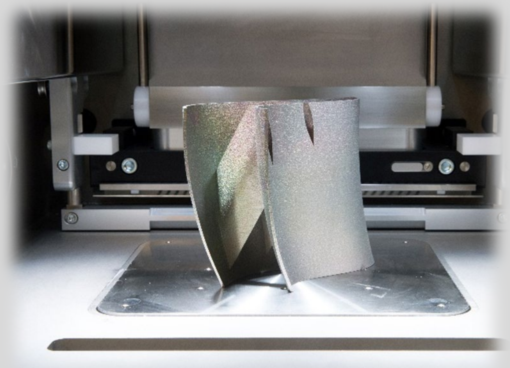
- This transformation process can be seen as an economical one: through usage of resources value is added by augmenting the original starting block.

- For most Additive manufacturing processes, the 'raw material' could also be understood as a resource input.

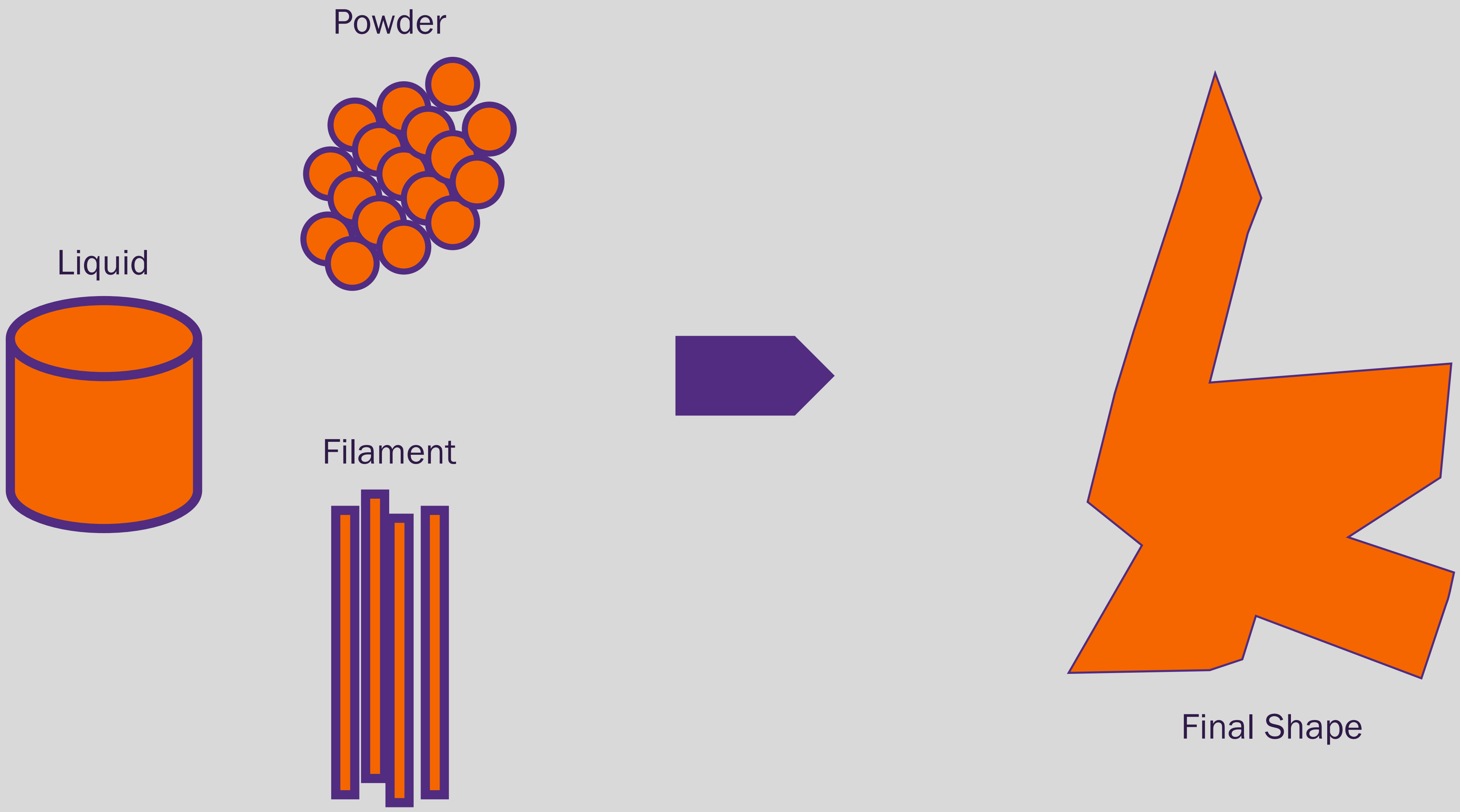


From the Raw Material ... to the Final Part





From the Raw Material … to the Final Part (abstract)



Generalized AM Process

- Additive Manufacturing requires a certain process to achieve the desired outcome.
- There are several steps that need to be followed before and after the actual AM process takes place.
- During the **engineering design** phase, specific limitations of AM have to be considered (e.g., support structure).
- In the preparation (**pre-processing**) phase, it must be checked if design contains critical flaws (e.g., gaps).
- In the aftermath, there is a (variating) amount of **post-processing** required.

Generalized process

Engineering Design
- Create CAD file
- Create STL-Data file

↓

Pre-Processing
- Preparation of files (e.g., close holes, support structure)
- Extracted layered model of design

↓

Additive Manufacturing
- Manufacturing of parts
- Control environment

↓

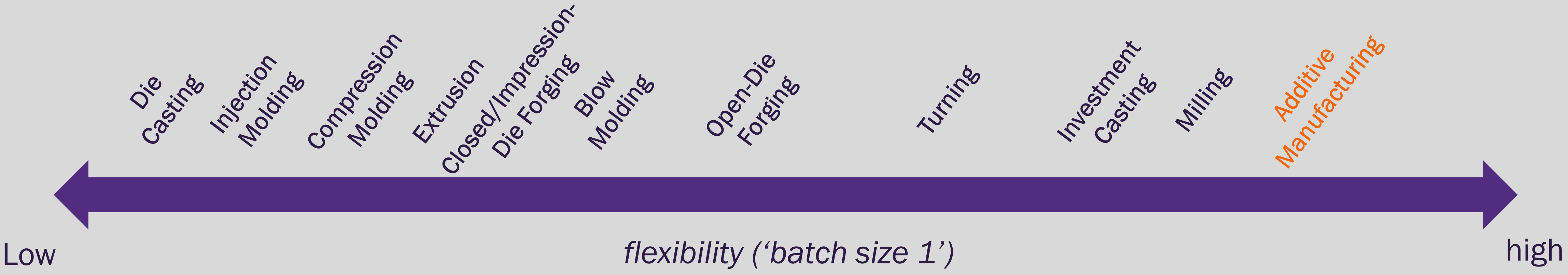
Post-Processing
- Remove support structure(s)
- Add. processes to achieve, e.g., tight tolerances (machining/grinding), desired material properties (sintering), surface finish (polishing/painting)

Classification of Additive Manufacturing

- Additive manufacturing is a highly flexible manufacturing process which is suitable for one-of-a-kind / small-batch size production runs

- No significant upfront cost (other than the system itself and design adaptation) like die-/mold-making required to ramp-up production

- However, cost per part are not significantly reduced with increasing batch size (-> limited effect of economies of scale)



Classification & Definition

- ASTM International **Committee F42 on Additive Manufacturing Technologies** defines Additive Manufacturing (AM) as:
- “A process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies.”
- The committee defines **7 different AM process categories** depicted on the right.
- We will focus on the **three AM processes** within the highlighted process categories in more detail.
- **Binder Jetting:** “[…] liquid bonding agent is selectively deposited to join powder materials.”
- **Direct Energy Deposition:** “[…] focused thermal energy is used to fuse materials by melting as they are being deposited.”
- **Material Extrusion:** “[…] material is selectively dispensed through a nozzle or orifice.”
- **Material Jetting:** “[…] droplets of build material are selectively deposited.”
- **Powder Bed Fusion:** “[…] thermal energy selectively fuses regions of a powder bed.”
- **Sheet Lamination:** “[…] sheets of material are bonded to form an object.”
- **Vat Photopolymerization:** ”[…] liquid photopolymer in a vat is selectively cured by light-activated polymerization.”

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General Pros & Cons of Additive Manufacturing

Advantages

- High degree of flexibility
- Ability to manufacture complex, near-net shapes
- Ability to manufacture assemblies
- Low ramp-up investment
- Reduced lead time
- Ability to manufacture multi-material/multi-color parts*
- Excellent mechanical properties*
- Little/No wasted material

Disadvantages

- Not economical for large batch sizes
- Manufacturing time required high*
- Skill and expertise needed to prepare design
- Requires post-processing (e.g., removal of support structure)
- Materials available limited & expensive (improving!)
- Systems (and maintenance) cost is high (improving!)
- Limited mechanical properties*
- Some waste materials can be hazardous*

**Highly dependent on selected process*

Evolution of Additive Manufacturing

1960s/1970s
- Research conducted in 2½D Rapid Prototyping, 3D printing etc.

1984
- Patent describing Stereolithography filed (granted in 1986)
- 3D Systems founded

1989
- Fused Deposition Modeling (FDM) patent filed (© by Stratasys)
- Alternative name: Fused Filament Fabrication (FFF)

2006
- First Selective Laser Sintering (SLS) system commercially available

2009
- MakerBot founded
- Acquired by Stratasys 2013
- Sold 100K+ 3D printers (April'16)

1960/70 — 1980 — 1990 — 2000 — 2010 — 2020

1981
- First account of rapid prototyping system on photopolymer basis in Japanese publication

1992
- 3D Systems develop first commercial Stereolithography (SLA) system

1997
- Selective Laser Sintering (SLS) patented (exp. 2014)
- However, first research / similar patents in 1980s

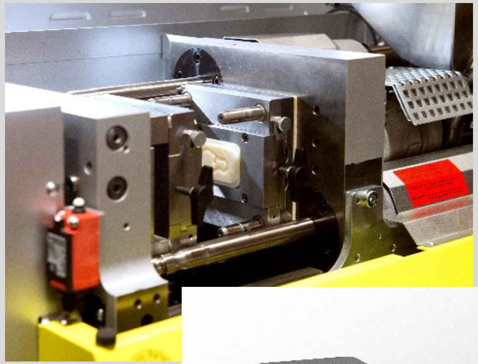
mid 2000s
- Patents started to expire and triggered new momentum in consumer and professional systems

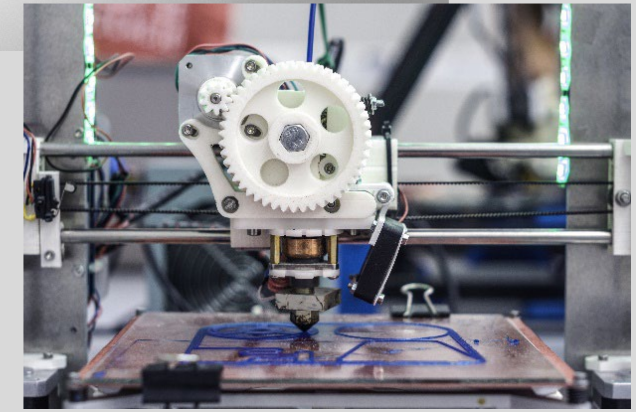
2014-2017
- SpaceX launches Falcon 9 rocket with multiple 3D printed essential parts & engine components

Application Areas (Selection)

Healthcare

Design/Manufacturing





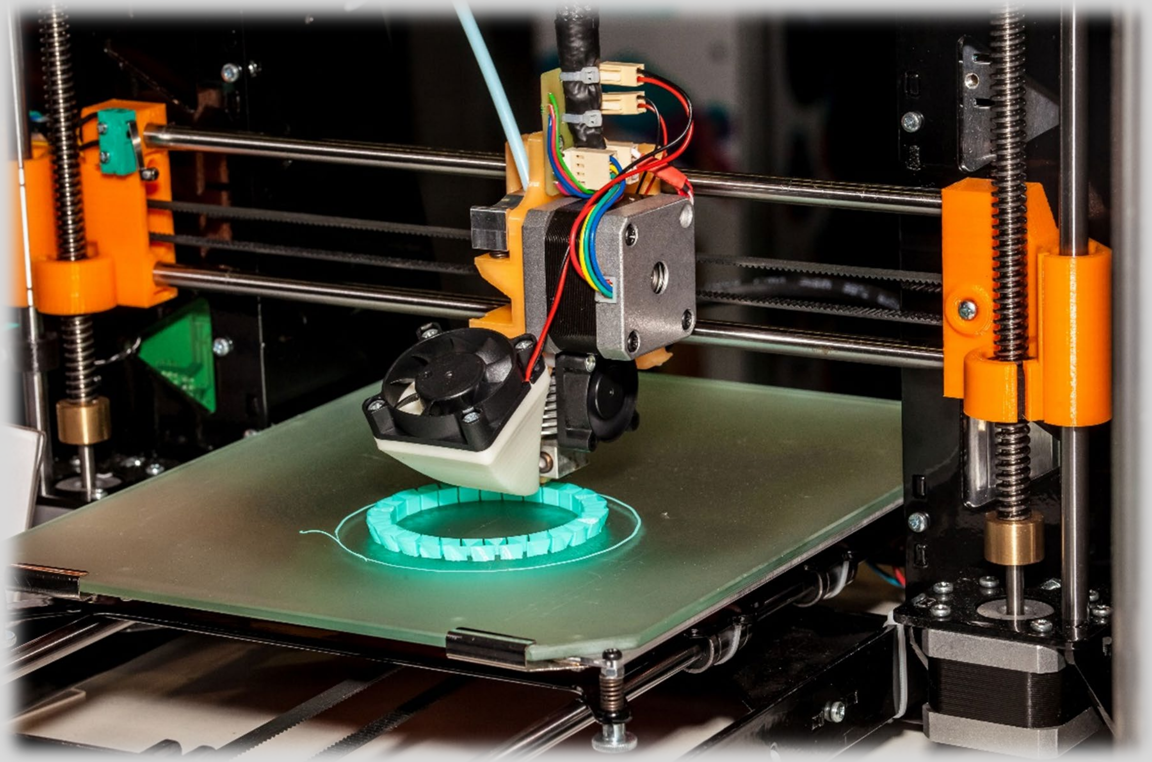
Aerospace

... and increasing!

Small to Large

System Parts

- **Fusion/Consolidation:** Usage of lasers, electron beams, extrusion heads to create the localized solid entity
- **Cut/restart:** Usage of mechanisms and cutting knives that enable the cut/restart process
- **Pressure:** Usage of pressure mechanisms in certain processes to 'sinter' components
- **Motion control:** Usage of mechanisms to ensure deposition/addition location and feedback to system
- **Containment Chamber:** Usage of volume separation to contain heat/cold depending on process. i.e. Cold chamber manufacturing.



Knowledge Check

Starting materials in additive manufacturing can be

A. Liquid Monomer
B. Metal Powder
C. Polymer Powder
D. Polymer Filaments
E. All of the Above

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Knowledge Check

A potential post processing function is to remove the support structures

A. True

B. False

Knowledge Check

A potential post processing function is to remove the support structures

A. True
B. False

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Material Classification

Section I

Additive Manufacturing vs Subtractive Manufacturing

- Subtractive Manufacturing
  - Milling (Prismatic)
  - Drilling (Axial)
  - Turning (Revolution)

- Additive Manufacturing
  - Filaments (FFF)
  - Powder (SLS)
  - Liquid (SL)

Starting Material

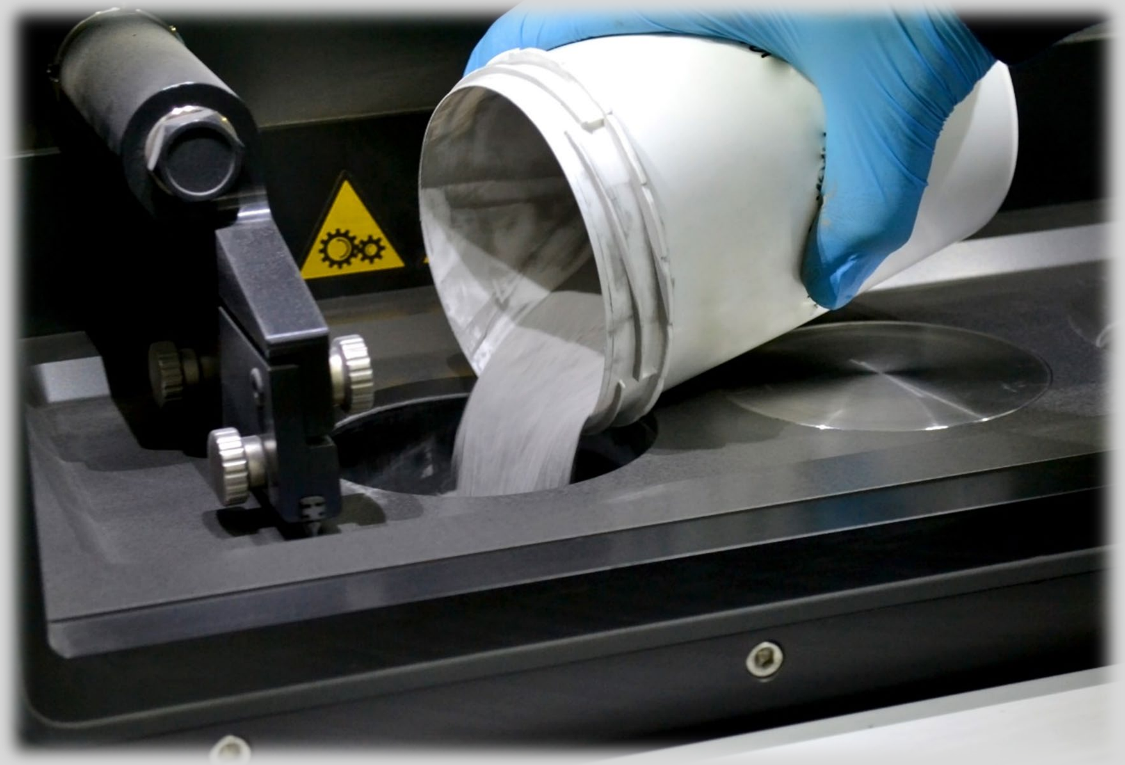
- Additive manufacturing processes are classified based on the starting materials in the process:
    - Filaments that are introduced by an extrusion head, and fused together constitutes family of Filament Fused Fabrication (FFF)
    - Powders that are spread and fused together using a laser or electron beam constitutes family of Selective Laser Sintering (SLS)
    - Liquid photopolymers that are available in a basin and are cured into solid polymers by means of laser constitutes the family of Stereolithography (SL) (sometimes referred to by the machine producing it as Stereolithography Apparatus (SLA))
- Additive Manufacturing provides a new level of ‘design freedom’ however there is the material challenge to overcome.

Filaments

- Filaments are widely available in a range of different qualities and prices
- Common filament materials:
  - Polylactic Acid (PLA)
  - Acrylonitrile Butadiene Styrene (ABS)
- Other filament materials:
  - Nylon / Reinforced nylon / Metal / carbon fiber / …
  - Polyethylene Terephthalate (PET) / Poly Propylene (PP) / Thermoplastic Polyurethane (TPU)
- Common filament sizes:
  - 1.75mm
  - 3mm

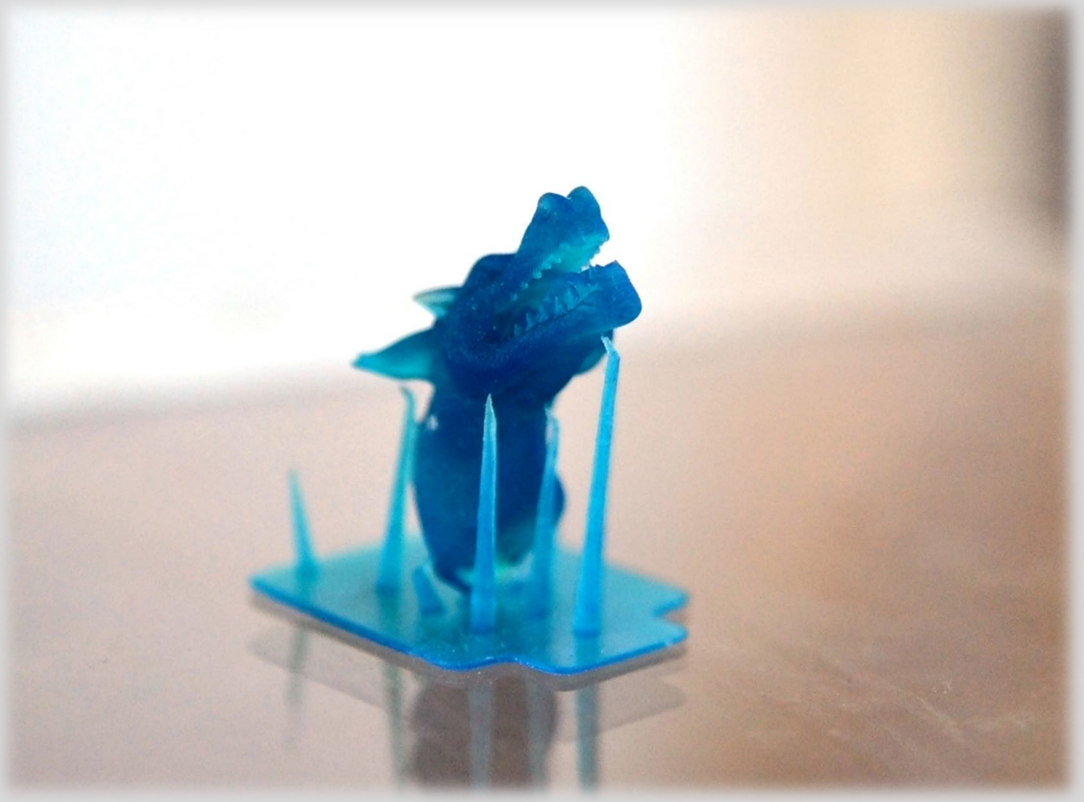
Powder

- Metal powder as a raw material for SL are increasingly available yet still **expensive**
- Depending on process, there might be certain **safety precautions** necessary
- Common **metal powder** variations:
  - Aluminum alloys
  - Cobalt based alloys
  - Nickel based alloys
  - Stainless steel / Tool steel
  - Titanium alloys
- Common **other powder** variations:
  - Ceramics (e.g., Silicon Carbide (SiC))
  - Polymers (e.g., Ultrasint PA6 - X028)



Liquid Photopolymers

- … are typically a mix of monomers with oligomers and photoinitiators.
- … are the raw material for the stereolithography process that solidify when cured by exposing them to UV light – typically using a UV laser – and thus become polymers.
- … are rather costly, however with a decreasing tendency.
- For liquid photopolymer a wide variation of specialized materials are trademarked and available only from the respective provider:
  - CeraMax (© 3D Systems): ceramic-reinforced composite
  - EPU60 (© Carbon): Elastic Polyurethane (EPU)
  - 18420 by SOMOS: Allows creation of RTV moulds
  - etc.



Knowledge Check

Filaments for Fused Filament Fabrication (FFF) are available in?

A. PLA
B. Nylon
C. Composite
D. Metal
E. All of the Above

Knowledge Check

Filaments for Fused Filament Fabrication (FFF) are available in?

A. PLA
B. Nylon
C. Composite
D. Metal
E. **All of the Above**

Knowledge Check

A wide variation of raw materials for all major additive manufacturing processes are readily available at low-cost.

A. True

B. False

Knowledge Check

A wide variation of raw materials for all major additive manufacturing processes are readily available at low-cost.

A. True

B. **False**

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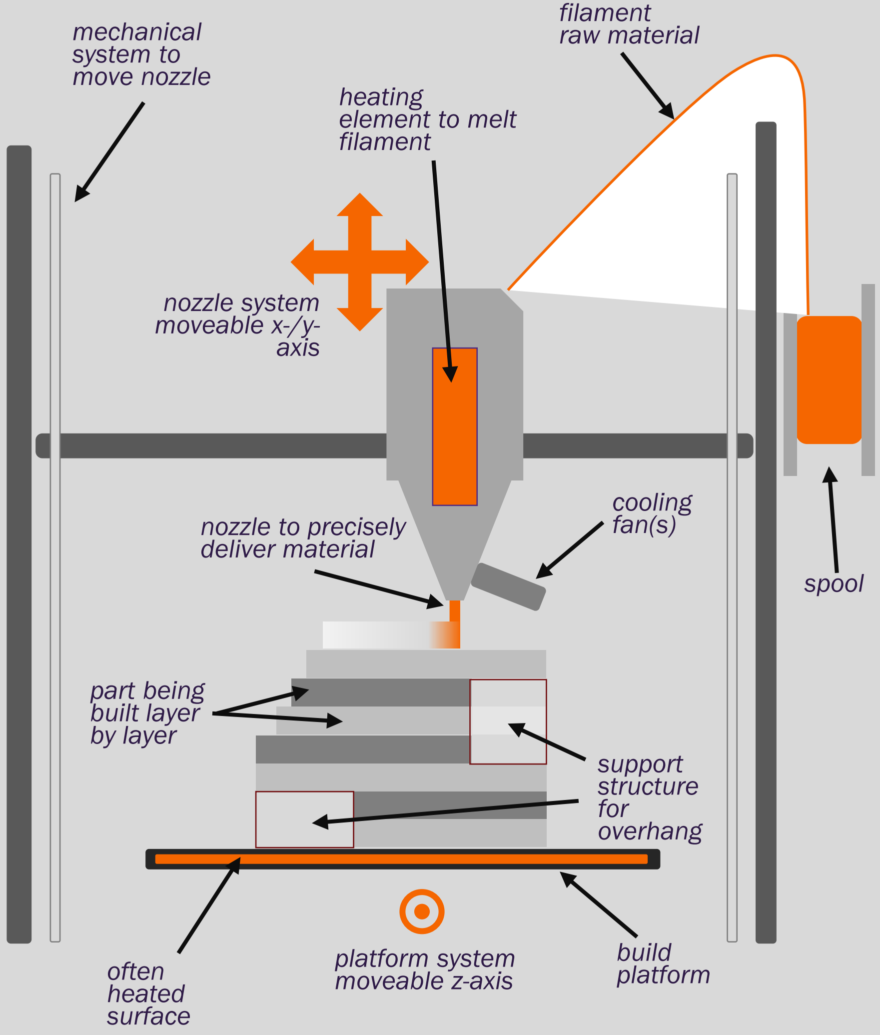
Fused Filament Fabrication (FFF)

Section II

Process

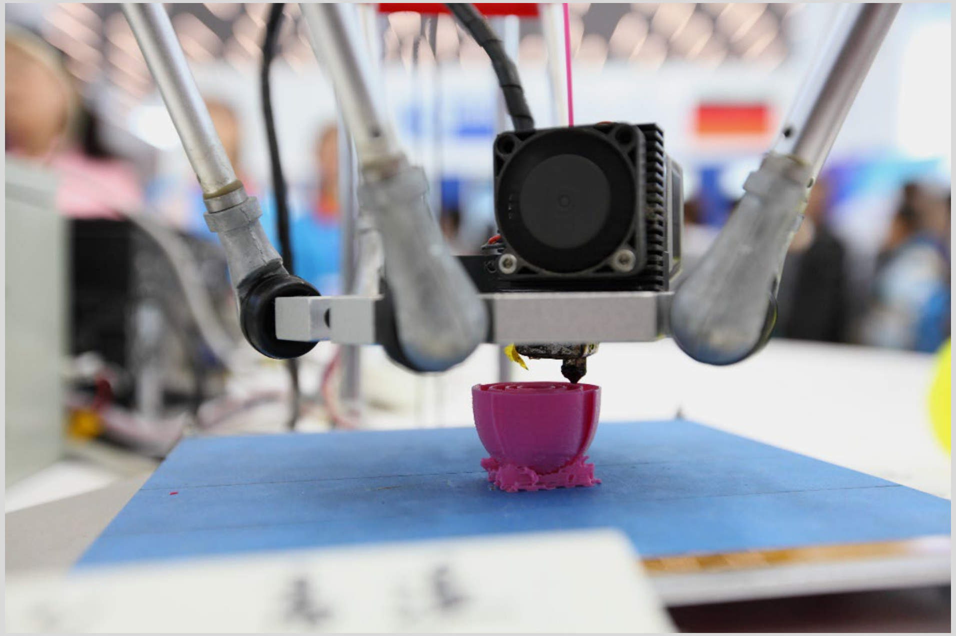
- Definition from ASTM Intl F2792-12a:
- Fused Filament Fabrication (FFF) is "a material extrusion process used to make thermoplastic parts through **heated extrusion and deposition of materials** layer by layer."
- Other commonly used and **closely related terms** are:
  - Fused Deposition Modeling (FDM) (© Stratasys)
- FFF processes are **widely in use** due to relatively low initial cost of the system, availability of low-cost materials and low maintenance

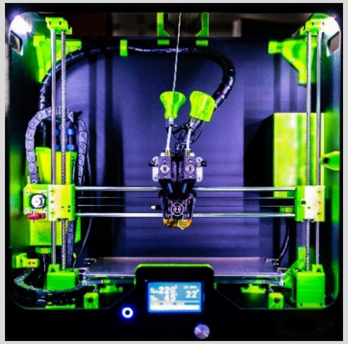


* different variations of combining mechanical systems to move nozzle / platform to achieve x/y/z reach

Tools

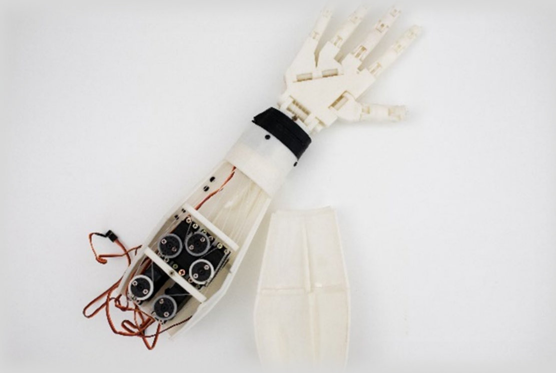
- Overall FFF is comparably low-cost / maintenance and thus most wide-spread
- Most common & available FFF system: MakerBot Replicator (various var.) can be bought ‘everywhere’, e.g., Sam’s Club (2016)
    - Resolution: 100 microns
    - Building Vol: Z18 11x12x18 in to mini+ 4x5x5
    - Variety of materials available (D=1.75mm)
    - Comparable low-cost (~$500 - $5,000) / Ease of use (offer own software suite) / plug’n’play
- Commercial systems (~$25,000 - $100,000+) like Stratasys Fortus 900mc allow for:
    - Larger build area (36x24x36 in)
    - More variety of materials & thus material properties
    - Smaller tolerances (=/- 0.0015 in/in) / build quality
    - Faster throughput





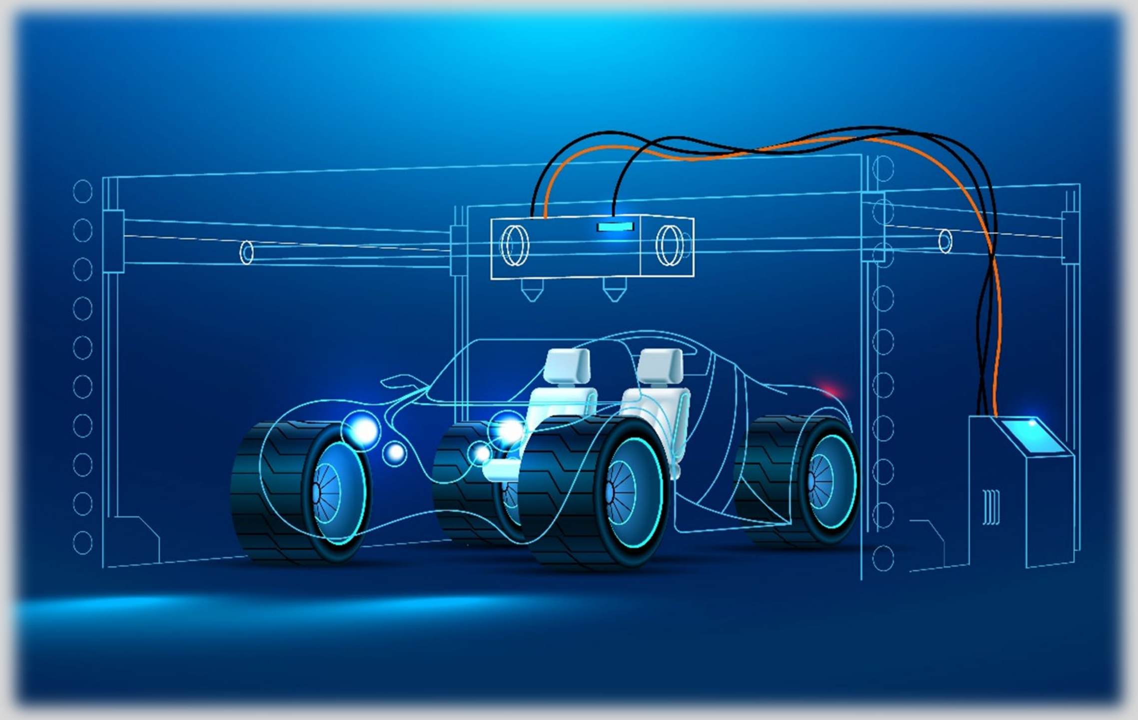
Application

- FFF can produce a variety of parts & products with a broad range of applications, ranging from designs, to prototypes & functional parts.
- Industrial
  - Automotive: transparent front/back light covers, mirror casings, etc.
  - Aerospace: lightweight composite (complex) parts; production fixtures
  - Manufacturing: job-shop production; tooling; fixtures
- Research
  - Rapid tools / fixtures for lab experiments
  - Visualize theo. concepts; replicate rare specimens (e.g., dinosaur skull)
- Education
  - Visualize 3D designs in STEM programs
  - Support for projects for students (e.g., robotics)
- Healthcare
  - Individualized support
  - Low-cost, rapid products (e.g., bionic hand)



Evolution and Impact

- 1988 - First prototype developed & patented (1989) as FDM by Scott Crump, founder of Stratasys, in the 1980s
- Idea came to Crump as he was creating a toy frog for his daughter using a glue gun
- 1990s - First commercial system available
- 2003 – FDM became the largest Additive manufacturing process
- 2012 – Stratasys merged with Objet
- 2013 – Stratasys acquires Makerbot
- 2014 – Stratasys 3d printed the exterior of an electric car with Objet1000



Knowledge Check

FDM is ...

A. FFF
B. SLS
C. SL

Knowledge Check

FDM is ...

A. FFF
B. SLS
C. SL

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Selective Laster Sintering (SLS)

Section III

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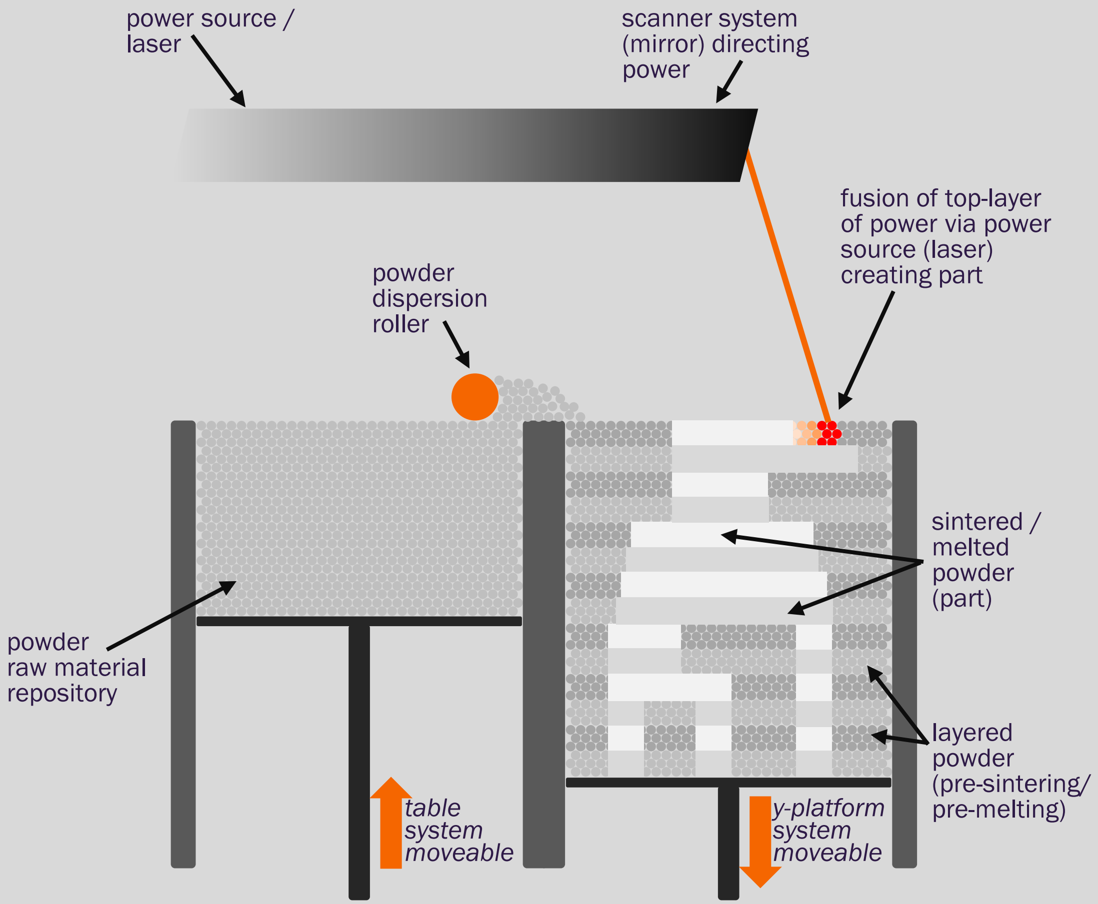
Process

- Definition from ASTM Intl F2792-12a:
- Selective Laser Sintering (SLS) is "powder bed fusion process used to produce objects from powdered materials using one or more lasers to selectively fuse or melt the particles at the surface, layer by layer, in an enclosed chamber."
- Other commonly used and closely related powder bed fusion processes are:
  - Selective Laser Melting (SLM)
  - Direct Metal Laser Sintering (DMLS)
- Historically, SLS and SLM are often used to describe the same process – however, some argue that
  - SLS is associated with polymer/ceramic powders
  - while SLM focuses on metal powders



Tools

- SLS tools are some of the most **expensive and complex** variation within the AM space.
- Just now, **first lower-cost variants** (e.g., Formlabs Fuse1 or Sinterit Lisa) are announced (pre-order) to entry prices around ~$13,000 - $$15,000.
- **Commercial/Industrial systems**
  - High cost
    - Investment (~$250,000 - $1,000,000+)
    - Maintenance (~$30,450/year) [1]
  - Example EOSINT P760 (~$800,000)
  - Medium build area (27.6x15x22.9in)
  - Limited selection of materials
  - Good resolution/layer thickness (min. 0.0024 in)/ build quality

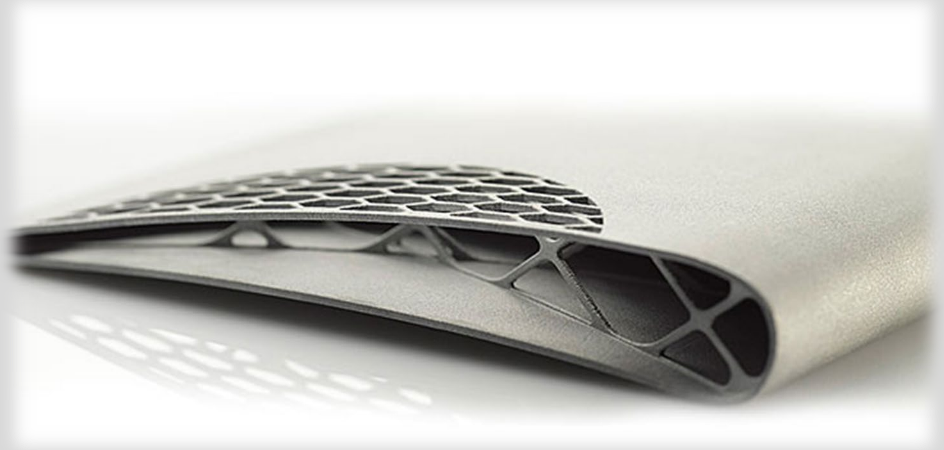
[1]

[1] NIST report - http://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1176.pdf

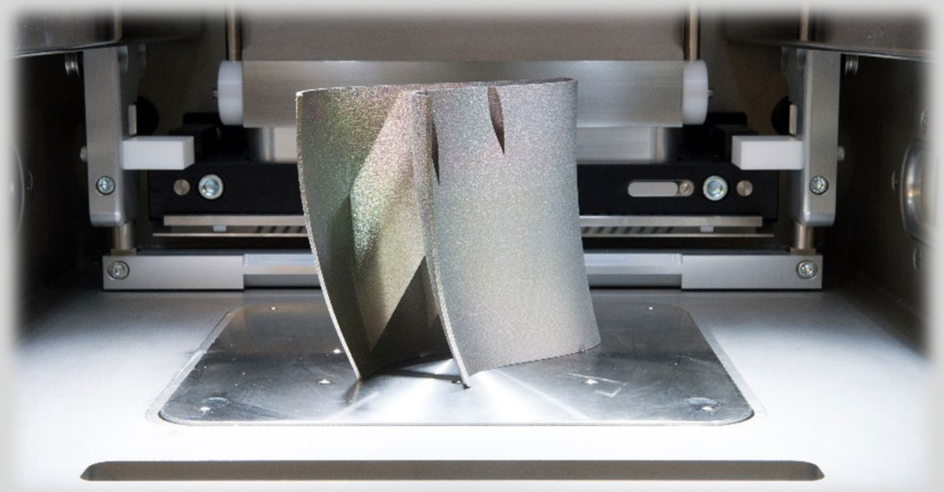
Application

- SLS, allowing for a wide variation of materials, (surface) finishes and high accuracy leads to **broad applications.**
- Possibility to directly create **fully functional parts/products** from metal, ceramic or polymer with good material properties
- **Industrial**
  - Automotive: Engine parts; structural parts, etc.
  - Aerospace: Integral propulsion system parts, etc.
  - Manufacturing: tooling; fixtures; etc.
  - Fashion: Clothes/shoes, e.g. Nike Vapor Laser Talon
- **Research**
  - Test prototypes of new innovative structures, etc.
  - New material/design combinations, etc.

[1]



[2]



[1] Courtesy Concept Laser GmbH
[2] https://www.helmut-fischer.com/fischer-blog/3ddc-success-story

Evolution and Impact

- 1989 – SLS invented by DTM (part of BF Goodrich)
- 1989 – SLS patented
- 1992 – First commercially successful systems launched: DTM SinterStation
- 2001 – 3D Systems acquires DTM
- 2008 – custom-fit prosthetics made by SLS
- 2014 – SLS patent expires
- XXXX – Desktop SLS printer

Knowledge Check

Powders for SLS can be

A. Metal
B. Ceramic
C. Polymer
D. All of the Above

Knowledge Check

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D. **All of the Above**

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Stereolithography (SL)

Section IV

Process

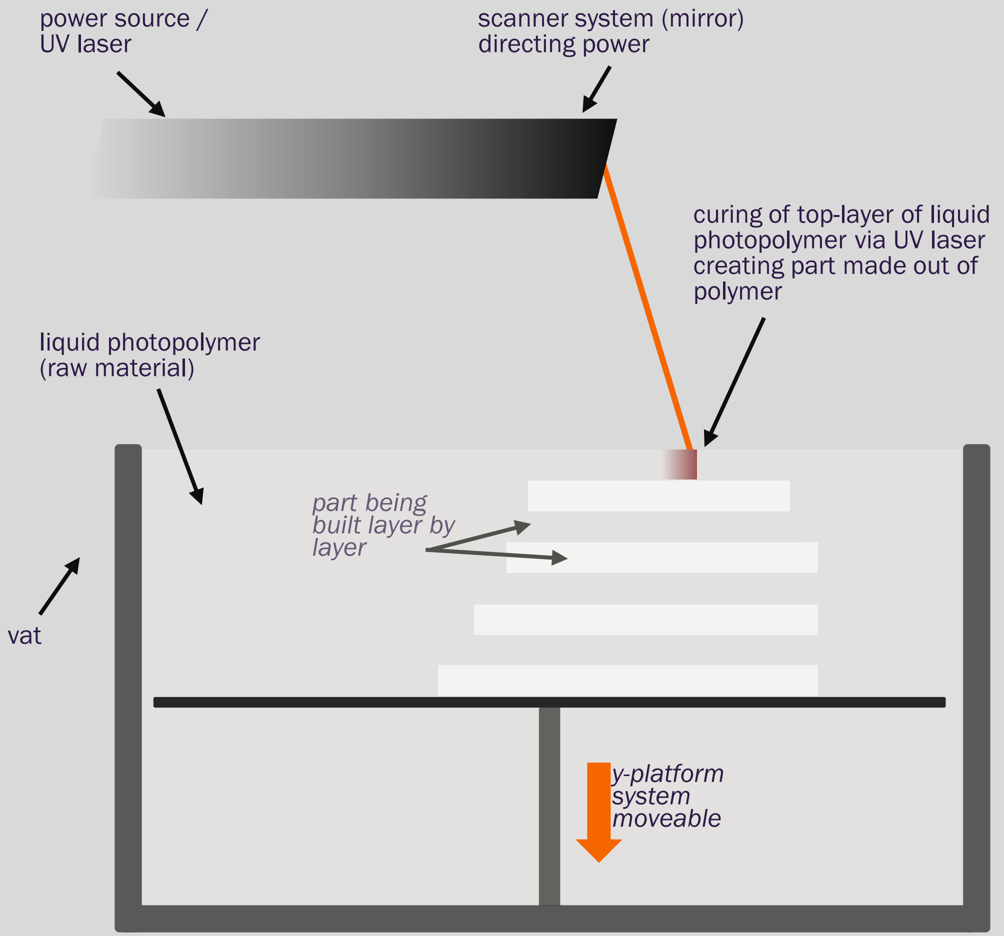
Definition from ASTM Int. F2792-12a:

- Stereolitography (SL) is “a vat photopolymerization process used to produce parts from **photopolymer materials** in a liquid state using one or more lasers to selectively cure to a predetermined thickness and harden the material into shape layer upon layer.”

- SL processes can manufacture products/parts with high surface quality from many materials.

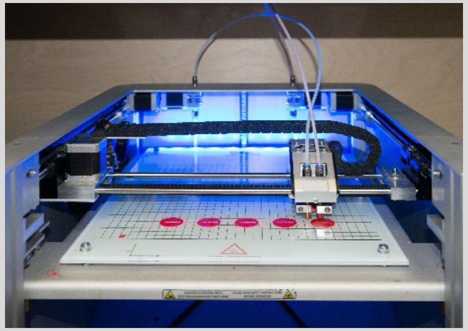
- Originally mainly used for **design and/or test prototypes**, today there are applications where a fully functional parts/products.

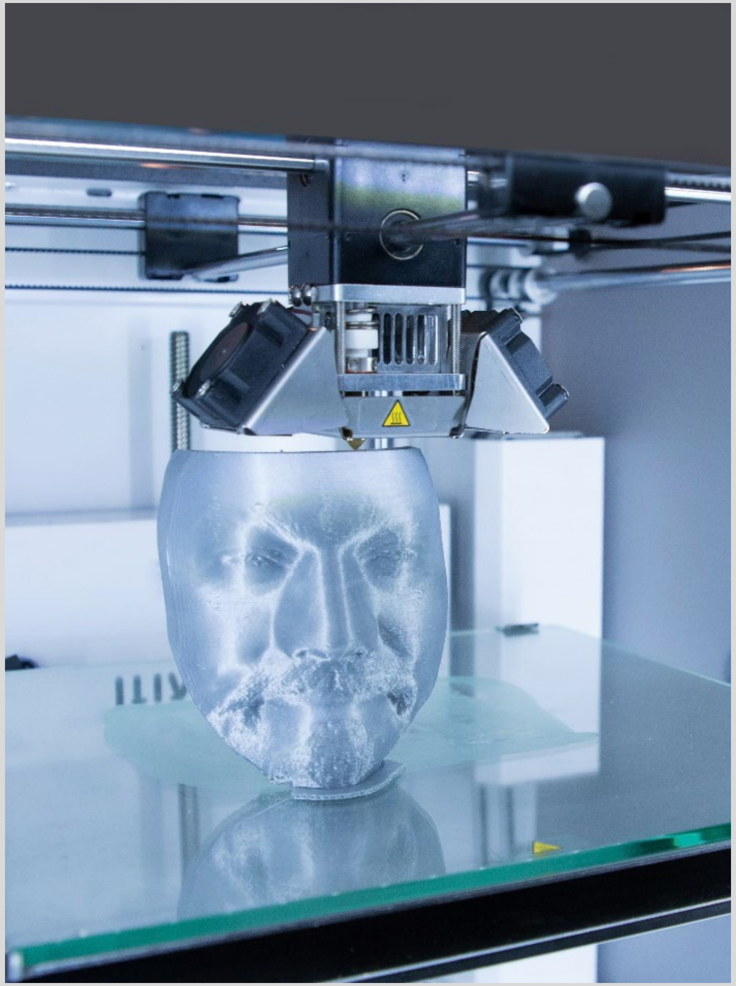
- Often are considered one of AM processes with highest (yearly) maintenance effort/cost.



Tools

- Previously, Stereolithography systems were comparably expensive and required high maintenance. In recent years, a few low-cost, low-maintenance systems emerged)
- Desktop variants (e.g., Formlabs Form1+/2)
  - Low-cost (~$3,000 - $7,000)
  - Resolution (layer thickness): 25 microns
  - Building Vol: Form2 13.5x13x20.5
  - Expensive and limited material availability
- Commercial/Industrial systems
  - High cost
    - Investment (~$50,000 - $1,000,000+)
    - Maintenance: (~$89,000/year) [1]
  - Example 3D Systems ProX 950
  - Large build area (59x30x22in)
  - Accuracy 0.001 mm

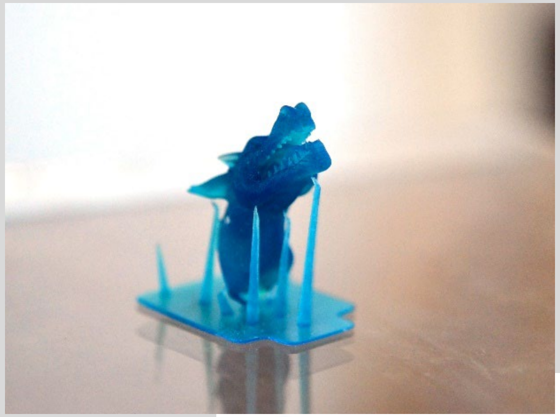




[1] NIST report - http://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1176.pdf

Application

- High build quality and an increasing variety of materials in combination with multi-material prints allow for a wide variation of applications.
- **Visual prototypes**
    - Great surface finish / variety of materials
    - Full engine design prototypes
- **Some (fully) functional parts**
    - Industrial casting molds
    - Materials can be cleaned and reworked – therefore, parts with (micro) structures are possible.
- **Test/functional prototypes**
    - Medical applications (e.g., test models for surgeons)
    - Dentistry



Evolution and Impact

- 1981 - First paper by Hideo Kodama, Japan, who also tried to patent process (unsuccessful)
- 1983 – First 3D printed part using FFF
- 1984 – SLA patented (1984 - U.S. Patent 4,575,330) by Charles Hull, USA, founder of 3D Systems Inc.
- 1987 - First commercial system available (3D Systems SLA-1)
- 1997 – EOS GmbH sells SLA business to 3D Systems

- Heat transmission channel evolving from 1D to 2D… to 3D
- New systems transmit 3D wave to obtain instantaneously the 3D model

Knowledge Check

Oligomers have the role to activate the polymerization

A. True
B. False

Knowledge Check

Oligomers have the role to activate the polymerization

A. True

B. **False**

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Process Planning and Tools

Section V

Model Flow in Additive Manufacturing

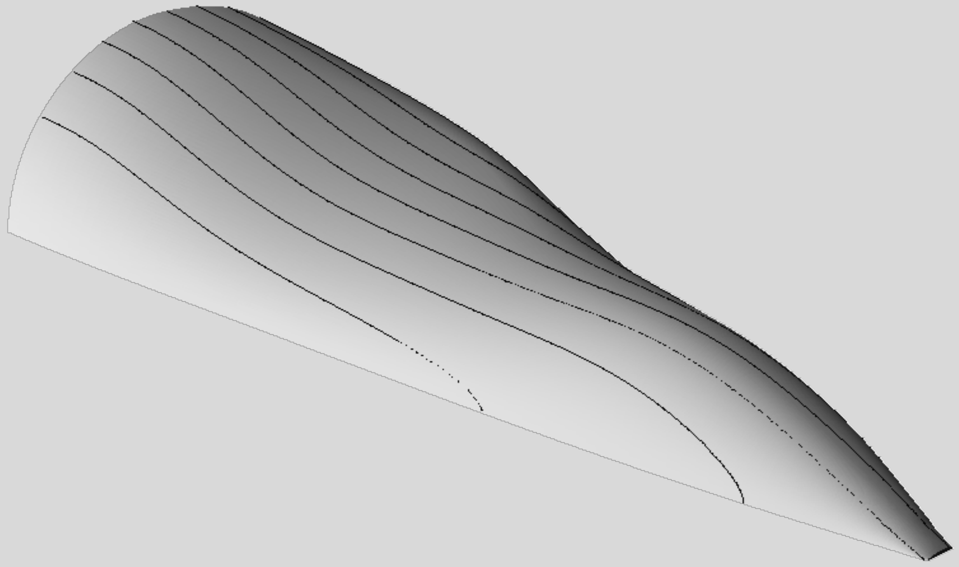
- In its most basic form, 3D printing includes three steps:
  - **Design:** Usage of CAD system to create a volumetric representation of the specifications at hand
  - **Tessellation:** Conversion of the CAD model into a format that approximates the topological boundary, most common conversion is into STL models
  - **Slicing:** As additive manufacturing is commonly built layer by layer, slicing algorithms are used to create these in-plane path. Current research is on out of plane additive manufacturing processes.

Process Planning in Additive Manufacturing

- Process planning is (AGAIN) the **matchmaker** between design and manufacturing.
- It is the single **most important step**, matching the design with the available resources.
- It includes multiple functions that can be separated as:
  - Material Boundary Topology **Optimization**
  - **Slicing** and Toolpathing
  - Optimal **Build Orientation**
  - **Grouping** of different parts in a single build
  - **Nesting** of different parts in a single build

Slicing

- Slicing transforms the solid CAD model of the to-be-manufactured part to the set of individual layers that will ultimately make up the part & defines the tool path.
- There are various software solutions available that aim to support the engineer during the slicing process & decision (freeware: Cura & Slic3r).
- There have to be some decisions made that have an impact on the final outcome of the part (printer speed; fill density; retraction; shell thickness/ layer height / initial layer height).
- An example of such a decision is the build quality (resolution). This defines the layer thickness and level of detail the printer will perform (one effect: low resolution/fast vs. high resolution/slow). Highly dependent on printer and material - some interesting research is being done in using build quality to secure digital files and prevent counterfeiting.
- There are several features that can cause problems during slicing - some will be discussed in more detail in the challenges section.

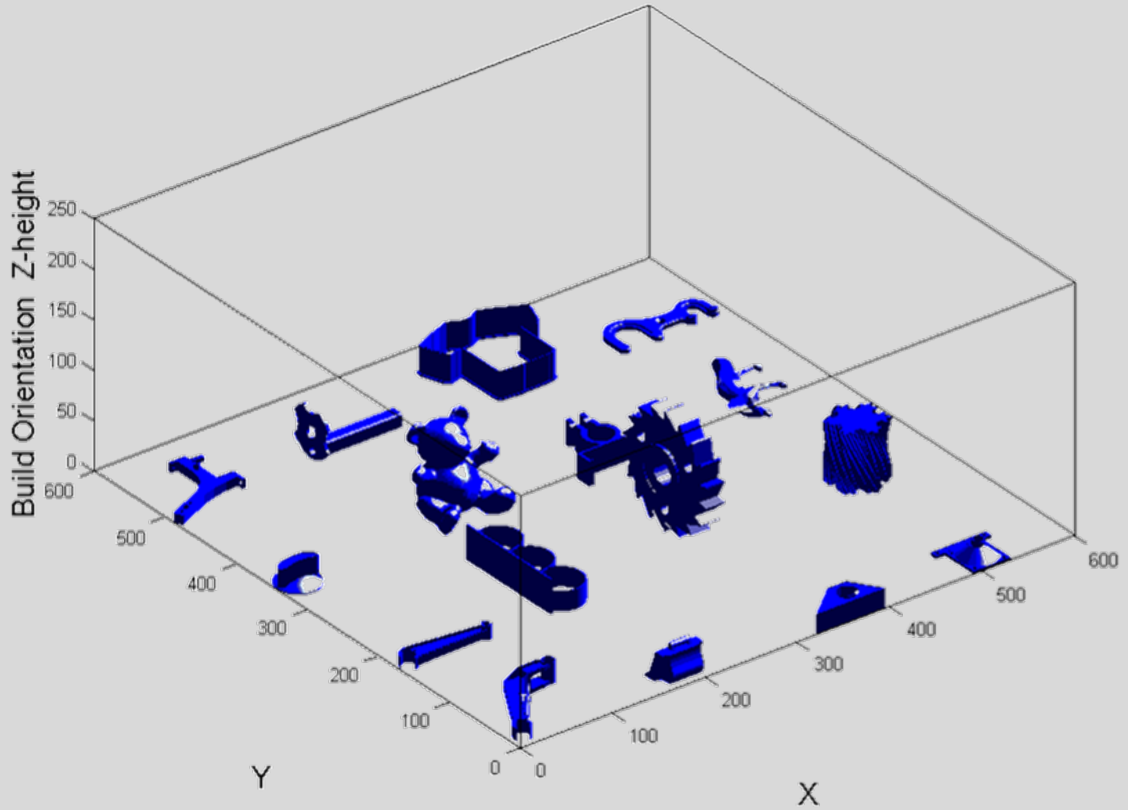


Halbritter et al

CADA 2016

Grouping/Nesting

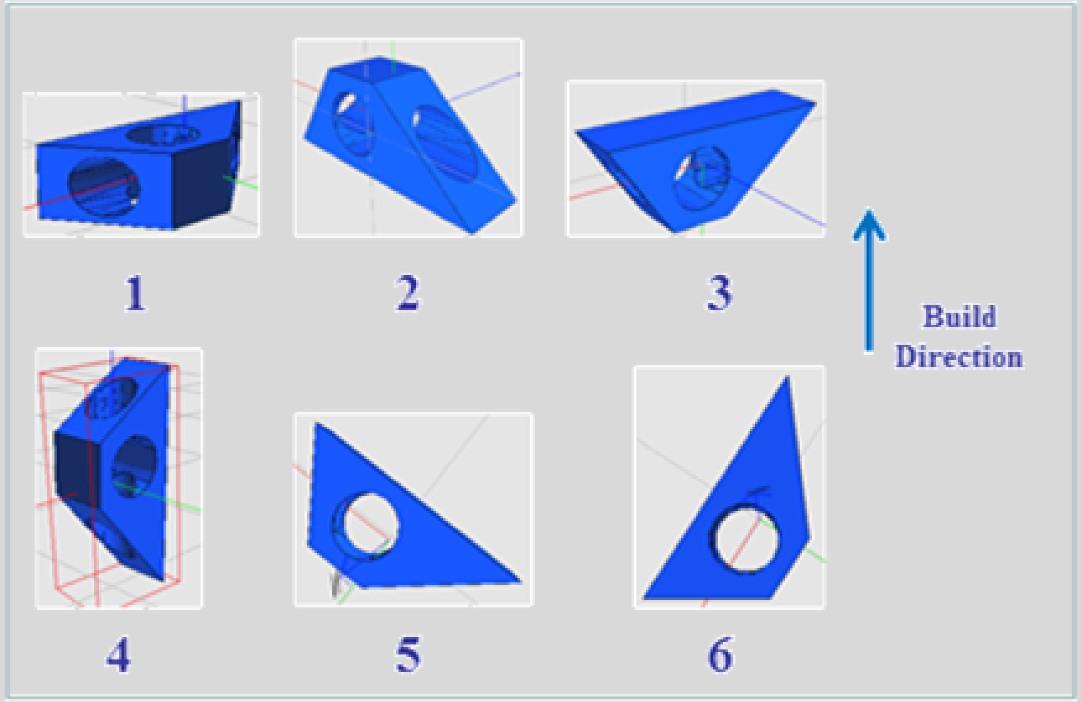
- Grouping describes the **strategic arrangement** of different (or multiple of the same) parts of an assembly to be printed in one setting.
- Well placed parts during grouping can significantly **enhance the output** of the AM process.
- Badly placed parts can not only 'waste' valuable AM capacity but also cause built **quality problems**.
- An example of such an arrangement that can cause quality issues is placing parts too closely together. Depending on the process (e.g., SLS), the dispersed energy can negatively effect the material property of too close placed part.



Zhang et al
RPJ 2015

Build Orientation

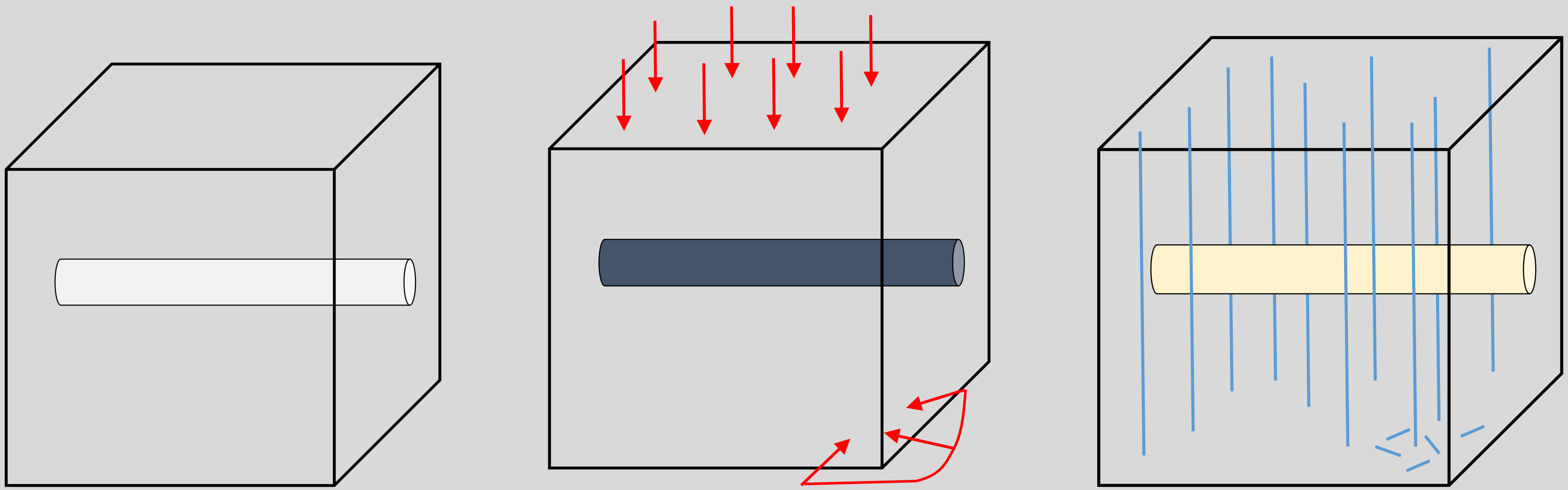
- Build orientation focuses on the virtual & physical placement of the part on the build platform.
- It is very important and have effect on multiple parameters like build quality, material properties of the printed part & even speed of manufacture.
- It has to be understood that slicing and build orientation depend on each other.
- Build orientation can have significant impact on how much support material/structure is needed. An experienced engineer can save significant rework and material waste by strategically using build orientation to optimize the support needed for overhangs and such.



Zhang et al
RPJ 2015

Topology Optimization

- Optimization of topology space based on functional requirements
- Shape is no longer the initial step, but rather the boundary conditions and mating/matching surfaces
- Algorithms to interpret the ‘grey’ matter, enhancing the performance of final part (stiffness and strength)



Knowledge Check

Slicing

A. Helps finding the optimal build direction
B. Identifies ways to enhance the part topology
C. Helps with Grouping functionalities
D. Supports the generation of toolpath

Knowledge Check

Slicing

A. Helps finding the optimal build direction
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Knowledge Check

Build Orientation Algorithms ...

A. Reduce the orientation space to an optimal set
B. Create for each feature 5 sets of directions
C. Support the selection of most suitable material

Knowledge Check

Build Orientation Algorithms …

A. Reduce the orientation space to an optimal set
B. Create for each feature 5 sets of directions
C. Support the selection of most suitable material

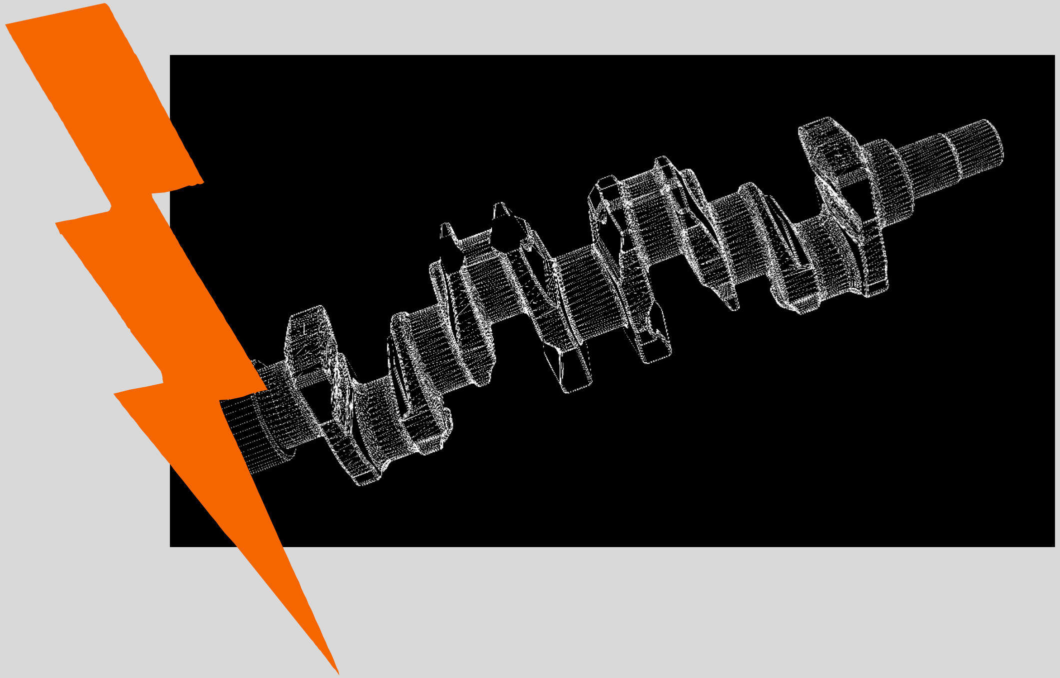
Clemson | CECAS | CCC | next

Challenges of Additive Manufacturing

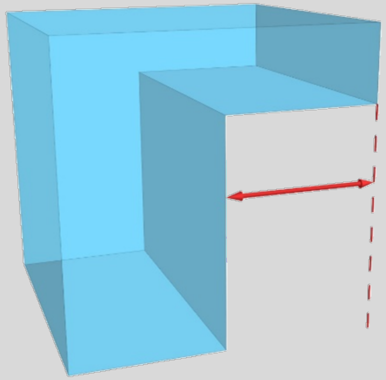
Section VI

Automated Manufacturability Analysis for AM

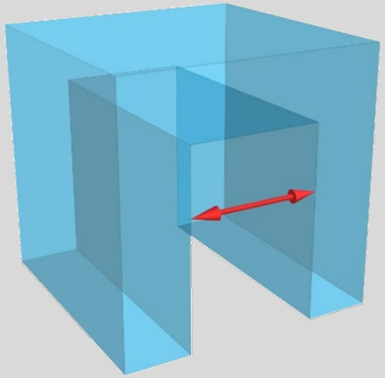
- ‘Non-manufacturable’ designs consume time and costs
- 3D Models for AM are usually complex
- Hardly any attempt to automated manufacturability analysis systems for AM
- Many professional guideline for designers
- Existing software solutions are limited to specific printers and/or types of errors
    - For example, duplicate vertices, self-intersections
    - None of them can handle geometric restrictions



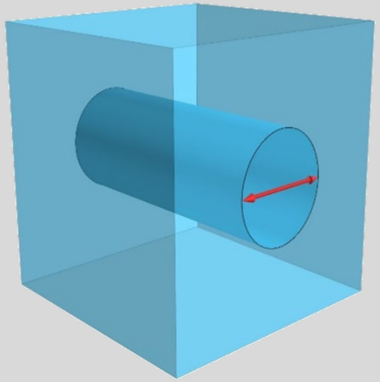
Considerable Features for AM



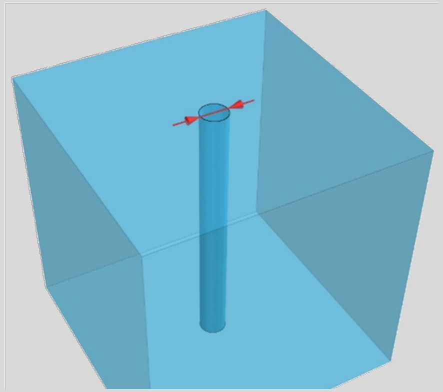
Overhangs without supports



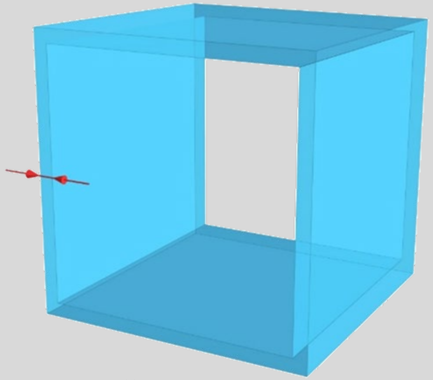
Bridges without supports



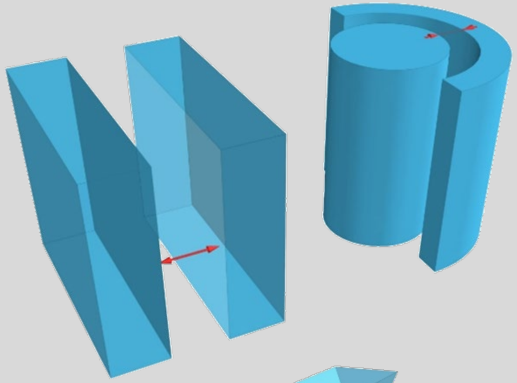
Maximum horizontal hole without supports



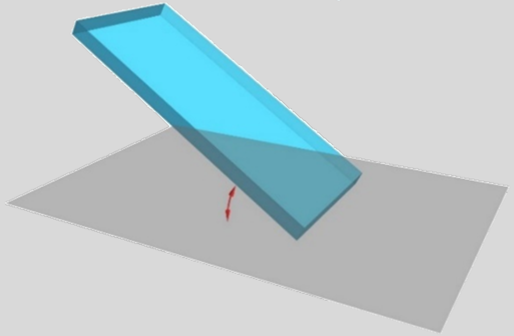
Minimum vertical diameter



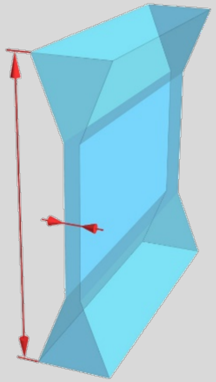
Minimum wall thickness



Minimum gap between surfaces



Minimum self-supporting angle

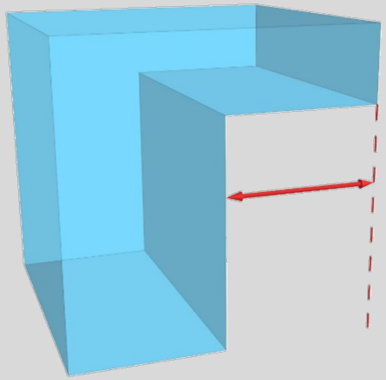


High aspect ratio

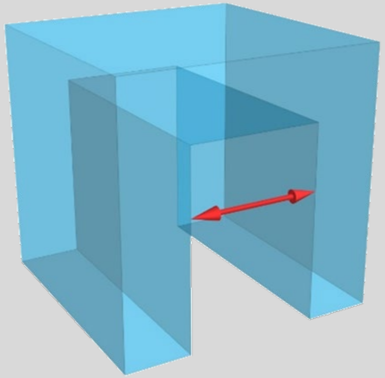
Unsupported Feature

- Fused Filament Fabrication (FFF) cannot extrude material above open air, so it requires external support structures for overhang, bridge and horizontal hole.

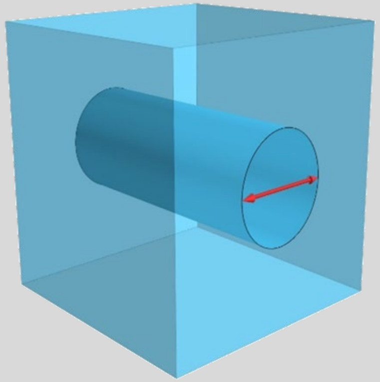
- The figure below shows these three types of unsupported features, and the red arrows mark the decisive dimensions involved.



Overhangs without supports



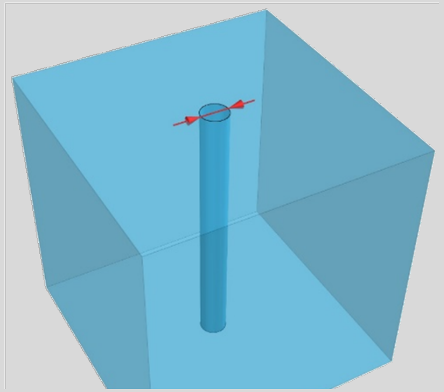
Bridges without supports



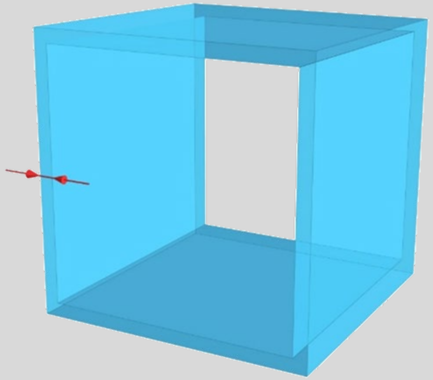
Maximum horizontal hole without supports

Minimum Feature Size

- In the additive manufacturing process, thin wall or small size structures are subject to significant thermal dissipation, which may cause various defects, such as
  - un-melted powder inclusions,
  - internal voids,
  - cracks and
  - shape irregularities.
- Therefore, it is necessary to specify a minimum dimension for thin wall and holes.



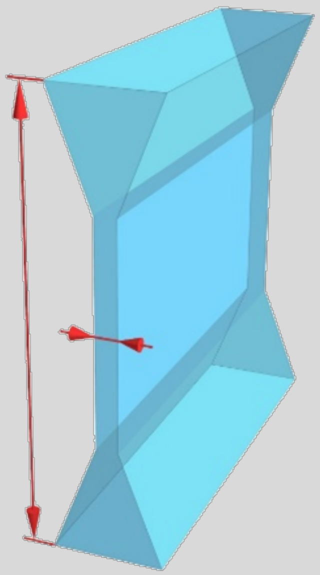
Minimum vertical diameter



Minimum wall thickness

Maximum Vertical Aspect Ratio

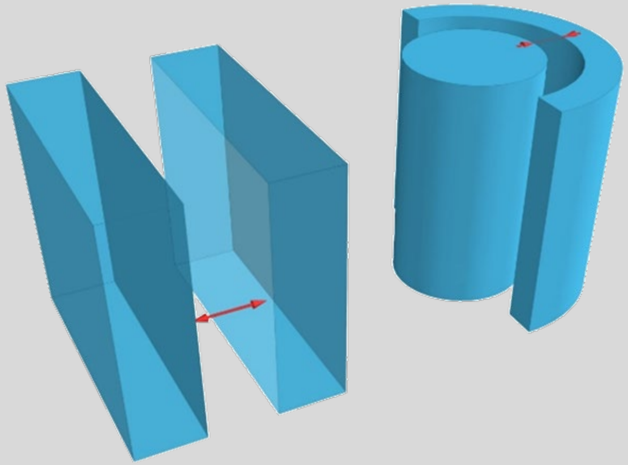
- Fused Filament Fabrication (FFF) feature cannot have a vertical aspect ratio exceeding a maximum value.
- The aspect ratio is defined as the proportional relationship between feature's height and width.
- Continuation of the recoating process will eventually result in the feature's bending.



High aspect ratio

Minimum Spacing

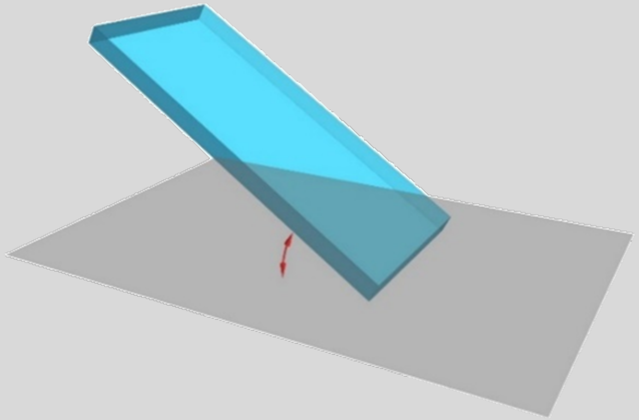
- In powder bed fusion (SLS/SLM) processes, if two surfaces are too close to each other, heat from one side may influence the properties of the other side.
- Therefore, it is necessary to specify a minimum spacing between two different surfaces.



Minimum gap between surfaces

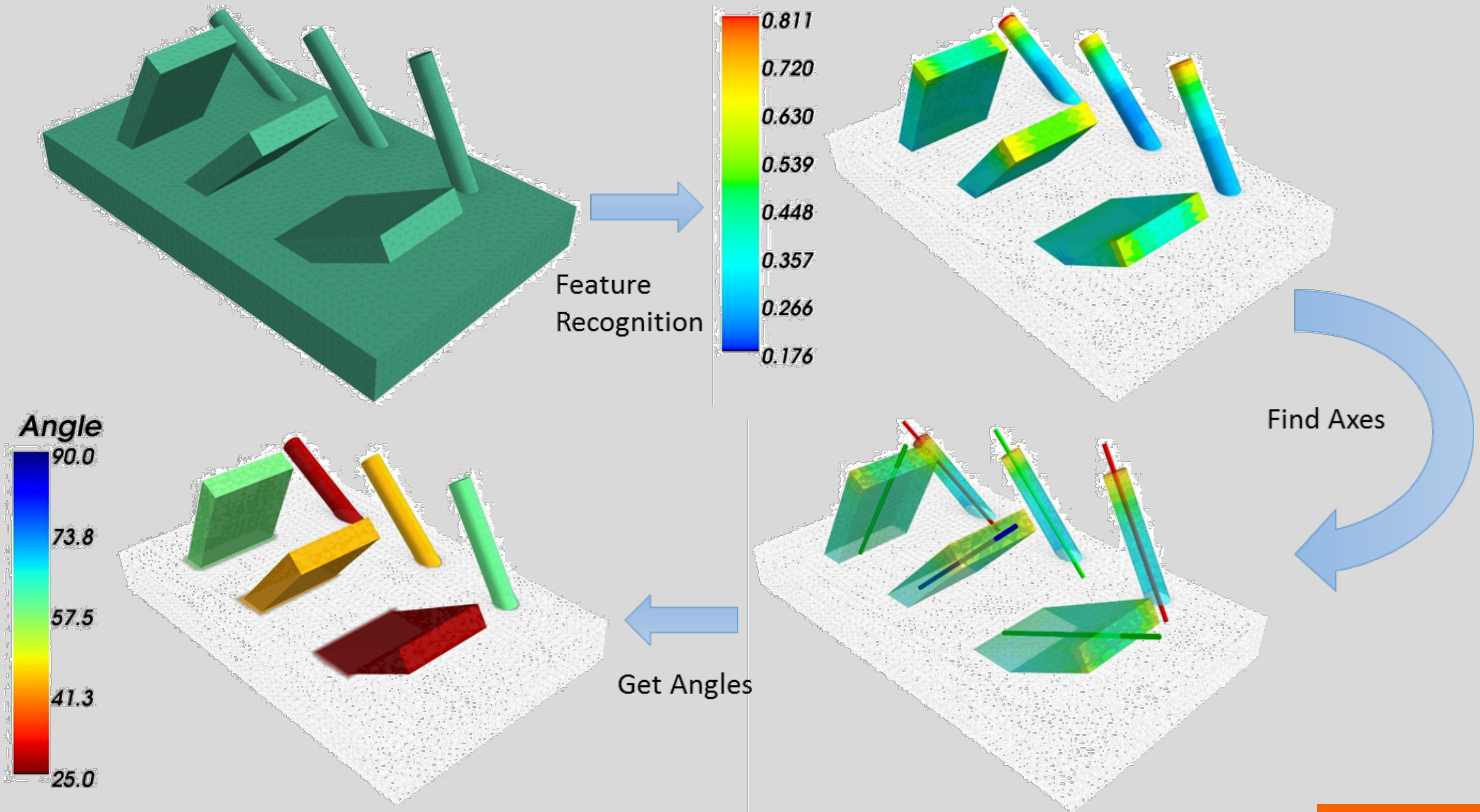
Minimum Self-Supporting Angle

- For Fused Filament Fabrication(FFF) features, it is necessary to set a **minimum inclination angle** to ensure that angled faces will **not collapse** without support material.



Minimum
self-supporting
angle

Algorithms for Detection of Challenges



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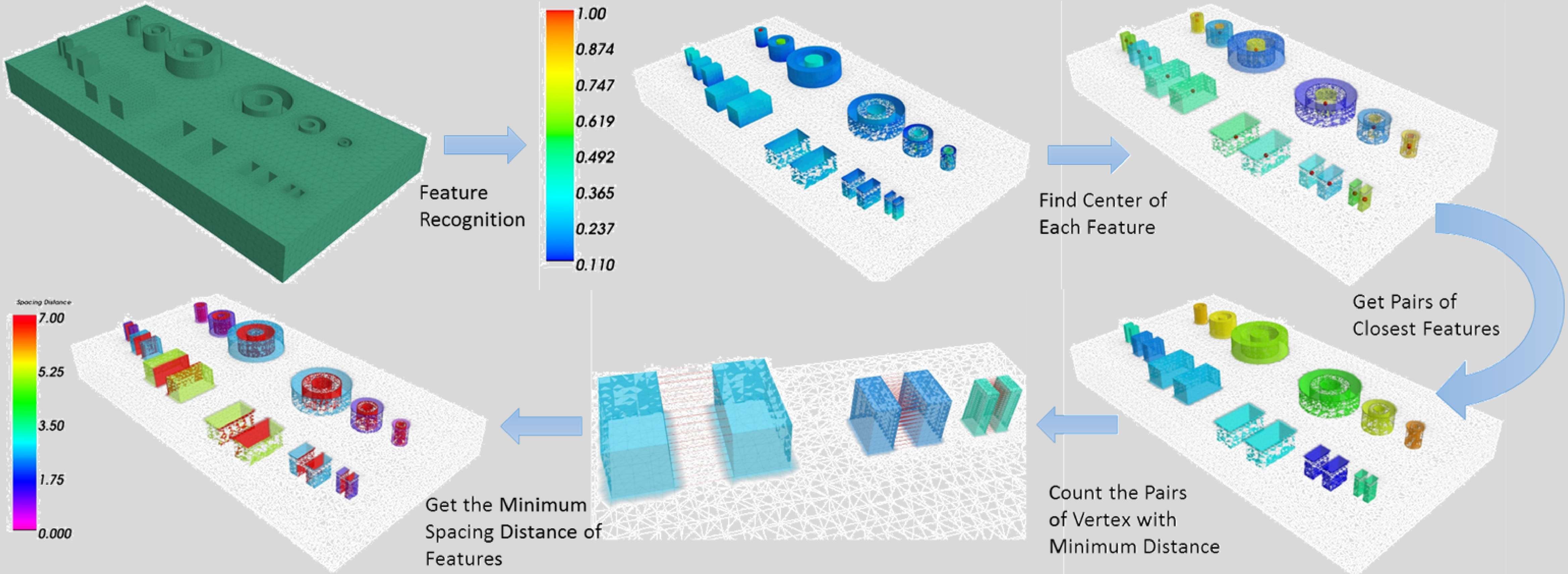
CADA 2017

Algorithms for Detection of Challenges



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Knowledge Check

Additive Manufacturing machines have limitations on the minimum size they can achieve.

A. True
B. False

Knowledge Check

Additive Manufacturing machines have limitations on the minimum size they can achieve.

A. True
B. False

Knowledge Check

Self-supporting angle investigation is needed for all additive manufacturing processes.

A. True
B. False

Knowledge Check

Self-supporting angle investigation is needed for all additive manufacturing processes.

A. True

B. **False**

THANK YOU

- This set of slides is retrieved from the textbook: Intro to Advanced Manufacturing, Harik/Wuest, ISBN 978-0-7680-9327-8 978-0-7680-9327-8
- Link of the textbook: https://www.sae.org/publications/books/content/r-463/
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