3D Printing and Additive Manufacturing

Pieper Smith and Ryan Lunas

Overview

- ★ What is 3D Printing/Additive Manufacturing?
- ★ 3D Printing Design Process
- ★ Algorithms of 3d Printing
- ★ Additive Manufacturing Applications
- ★ Emerging Techniques/Recent Advancements
- ★ Conclusion

What Is 3D Printing?

What is 3D Printing?

- ★ Additive Manufacturing (AM) is defined in the ISO/ASTM 52900 standards document as the "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies".
- ★ Subtractive manufacturing is the reverse, where the process makes the part by removing materials.
- ★ Formative manufacturing is the process of using a mold or form to create the part.

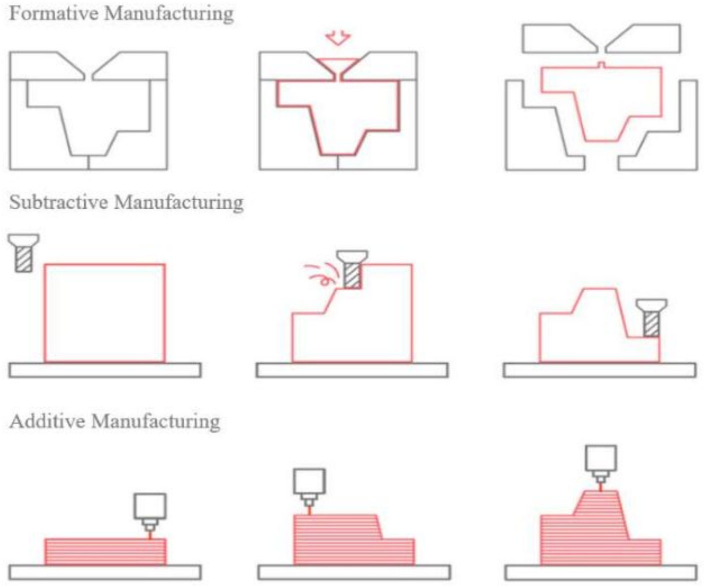
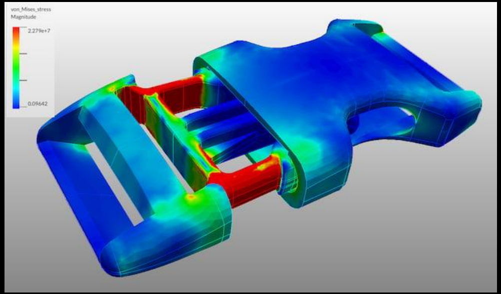


Figure 1.1 Formative, subtractive, and additive manufacturing processes (Redwood *et al.*, 2017).

3D Printing Design Process

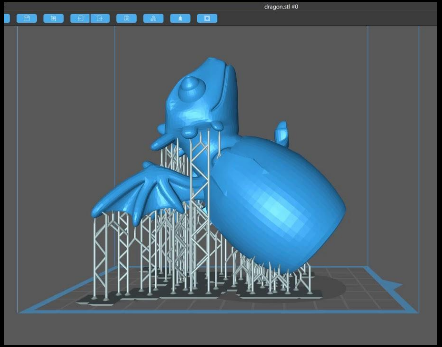
CAD Software



3D Modeling Software

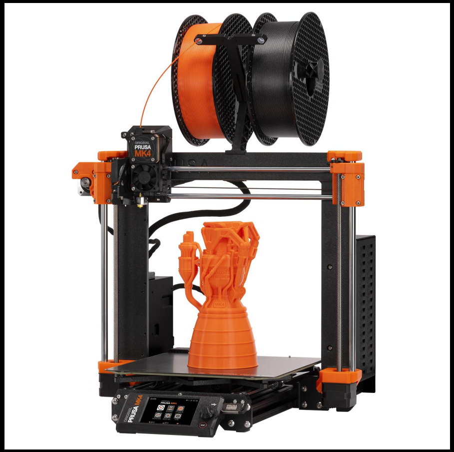
STL OBJ
AMF 3MF

Slicing Software



G-code

3D Printer



From left to right, top to bottom:
https://fractory.com/finite-element-analysis-software/
Utah Teapot - Wikimedia Commons
https://i.ytimg.com/vi/3Q5MUVmb_ZE/maxresdefault.jpg
https://www.prusa3d.com/category/3d-printers/

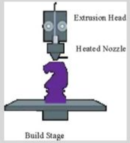
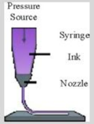
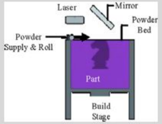
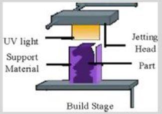
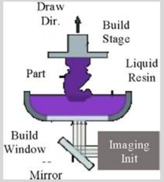
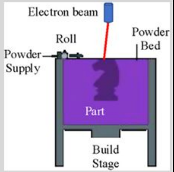
3D Printing Techniques

Karakurt, Ilbey, and Liwei Lin.

- ★ Fused deposition modeling (FDM)
- ★ Direct ink writing
- ★ Selective Laser Sintering (SLS)
- ★ Inkjet Printing
- ★ Stereolithography (SLA)
- ★ Digital light processing (DLP)
- ★ Electron beam melting
- ★ Multiphoton polymerization (aka photopolymerization)
- ★ Selective Laser Melting (SLM)
- ★ Laser Metal Wire Deposition (LMWD)
- ★ LOM (Laminated object manufacturing)

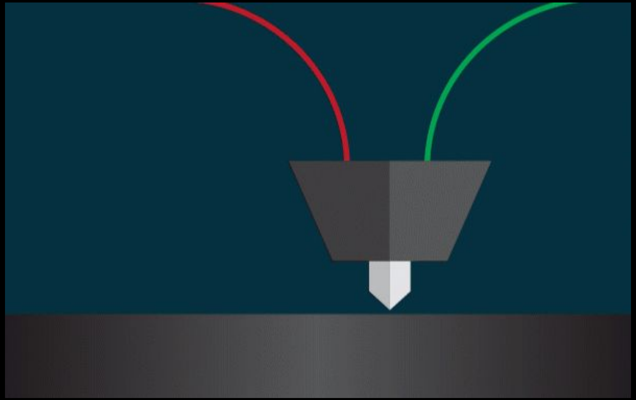
Table 1

Overview of widely used 3D printing techniques

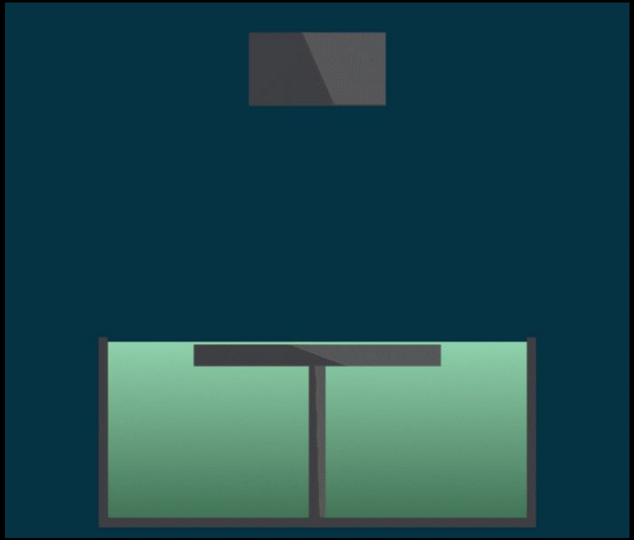
	Fused deposition modelling	Direct ink writing	Selective laser sintering	Inkjet printing	Stereolithography and light-based systems	Electron beam melting
Illustration						
x -y resolution	100 μm	1–100 μm	1–100 μm	10–100 μm	100 nm–100 μm	1–100 μm
Materials	Thermoplastics cement	Hydrogels, composites	Metals and polymers	Methacrylate based polymer networks	Photocurable polymers networks	Metals and metal alloys
Application areas	• Micro-fluidics, • Soft robotics • Prosthetics, • Composite ceramics, • Composite metallic	• Hydrogels for soft robotics • Hydrogels for drug encapsulation • Tribo-electric touch sensors • Ceramics for optics • Cellulose nano-crystals	• Soft robotic hand and soft systems • Turbine blades • Engines, brakes • Prosthetics and implants • Vacuum electronic devices	• Microfluidics, • Soft robotics, • Structural components, • Sensors, actuators, and energy harvesters.	• Microfluidics, • Soft robotics, • Micro pillars, fibers, and springs for cell studies	• Aerospace, • Vacuum electronic devices, • Energy systems

3D Printing Techniques

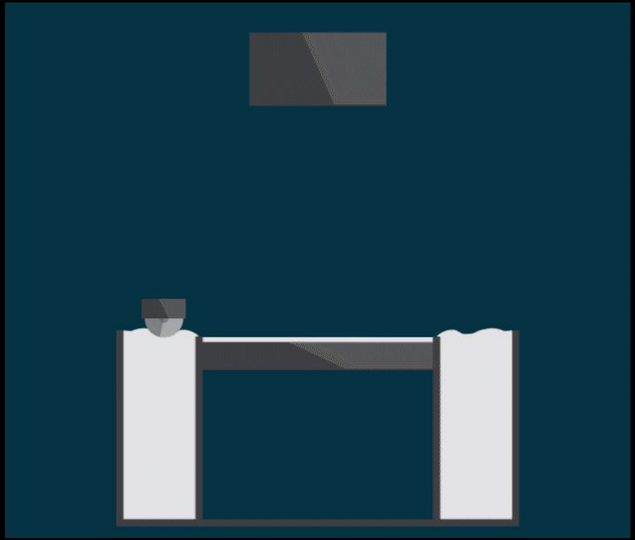
Fused Deposition Modeling (FDM)



Stereolithography (SL)



Laser Sintering (LS)

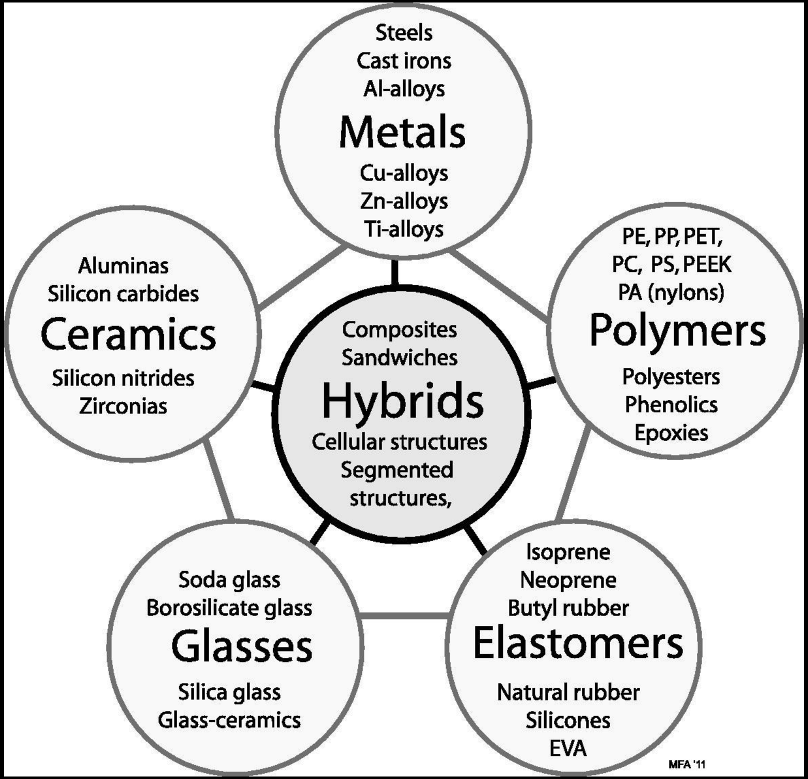


https://www.nazdar.com/en-us/News-Press-Releases/ArtMID/4163/ArticleID/399

3D Printing Materials

There are many additive manufacturing materials. They are broadly classified as solid-based, liquid-based, and powder-based. Many of the materials can take multiple forms, dependent on their processing and the printing conditions.

- ★ Shape memory alloys (SMA)
- ★ Ferrofluid
- ★ Magnetorheological (MR) fluids
- ★ Electroactive polymers (EAPs)
- ★ Piezoelectric materials
- ★ Chromogenic materials
- ★ Bioinks

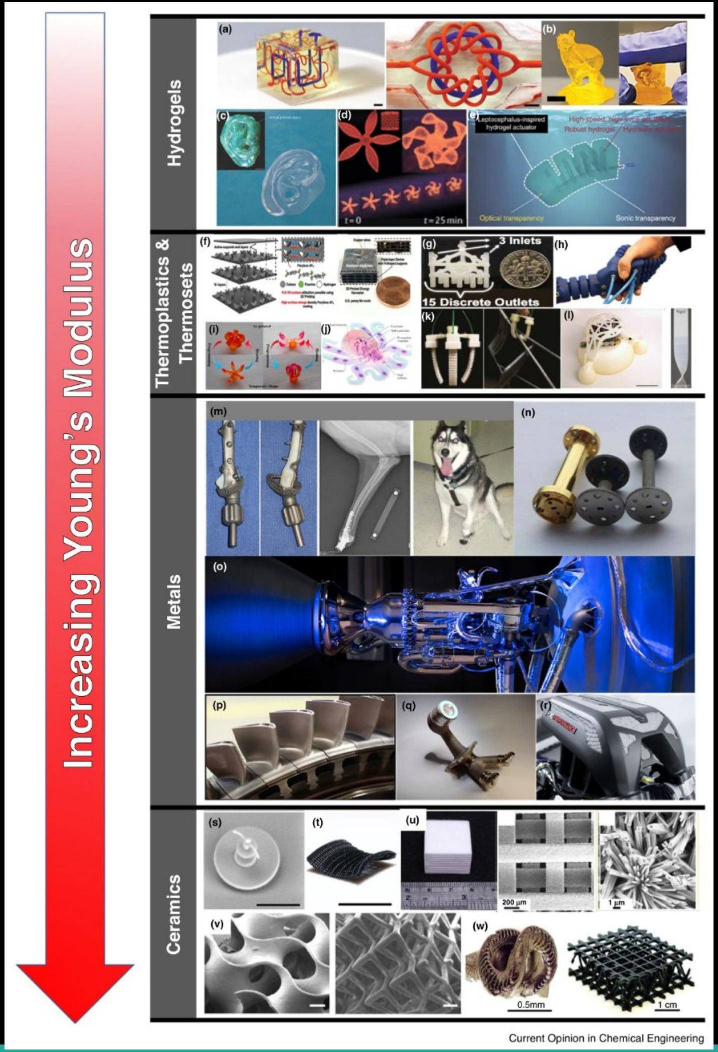


Ashby, Mike.

3D Printing Materials

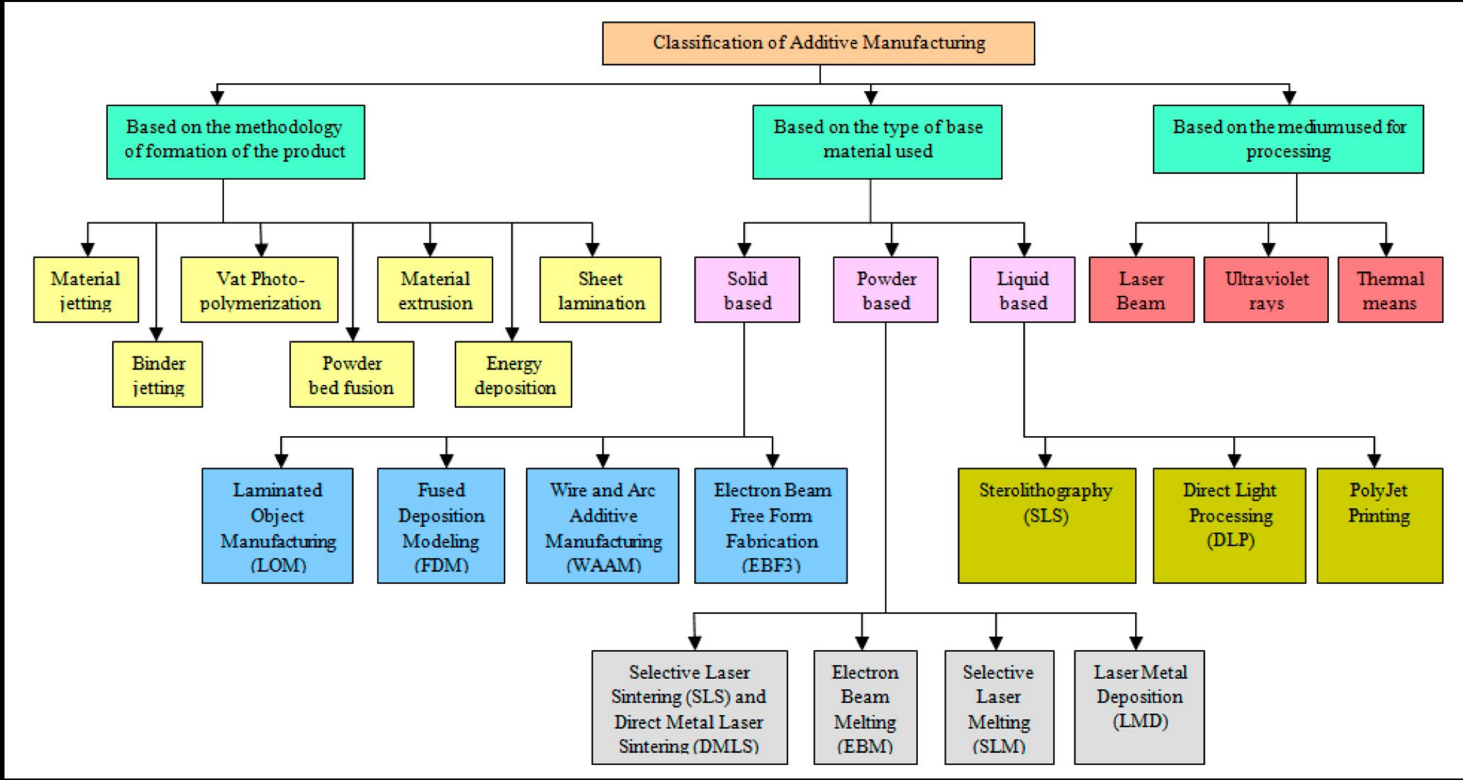
“Young’s modulus is a measure of the ability of a material to withstand changes in length when under lengthwise tension or compression.”

The properties that different materials have make them suitable for creating parts for specific applications. For this reason, there is a huge number of materials used in additive manufacturing processes. Most consumer-grade 3D printers use fused deposition modeling with solid polymer filaments.



https://www.britannica.com/science/Youngs-modulus
Karakurt, Ilbey, and Liwei Lin.

Techniques and Materials Summary



Saleh Alghamdi et al.

History of 3D Printing

1960s-1980s: Foundational research and developments in additive manufacturing (AM). The invention of photopolymerization.

1987: Stereolithography (SL) is introduced for commercial use by 3D Systems with the SLA-1 system.

1988: A partnership between 3D Systems and Ciba-Geigy advances SL materials, resulting in the commercial release of acrylate resins. DuPont and other entities improve their stereolithography machines and materials. Fused deposition modeling invented.

1989: NTT Data CMET and Sony/D-MEC in Japan, among others, introduce their versions of stereolithography to the market.

1990-1991: Stratasys debuts its version of Fused Deposition Modeling (FDM), alongside other AM technologies such as SGC (Solid ground curing) and LOM (Laminated object manufacturing). DTM develops Selective Laser Sintering (SLS).

The 3D Systems SLA-1. Photo by Michael Petch.

History of 3D Printing

1992-1994: Many advancements in machines and materials, with companies like Soligen and Denken launching new AM systems.

1996: The market sees the introduction of low-cost 3D printers by Stratasys, Z Corp., and others.

1997-2005: A surge in the commercial availability and application of various AM technologies, including the launch of EOSINT machines by EOS and advancements in direct metal deposition. First uses in bio-medicine.

2006-2012: The applications of AM expand significantly, with advancements in materials and processes, and the introduction of multi-material printers. First 3D printed blood vessel.

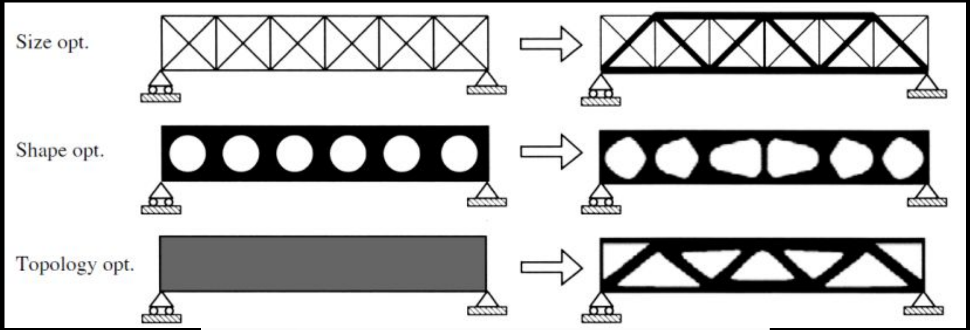
2013-2015: Significant progress in metal additive manufacturing, with companies like GE integrating AM for essential components. First 3D printed house.

multistation.com

3D Printing Algorithms

3D Printing Algorithms

Gebisa, A. W., and H. G. Lemu.



Topology Optimization - "Topology optimization (TO) is a shape optimization method that uses algorithmic models to optimize material layout within a user-defined space for a given set of loads, conditions, and constraints."

Generative Design - Uses machine learning techniques to make a part from scratch that fits the constraints.

Toolpath Optimization - Uses algorithmic models to find the most efficient path for tool travel.

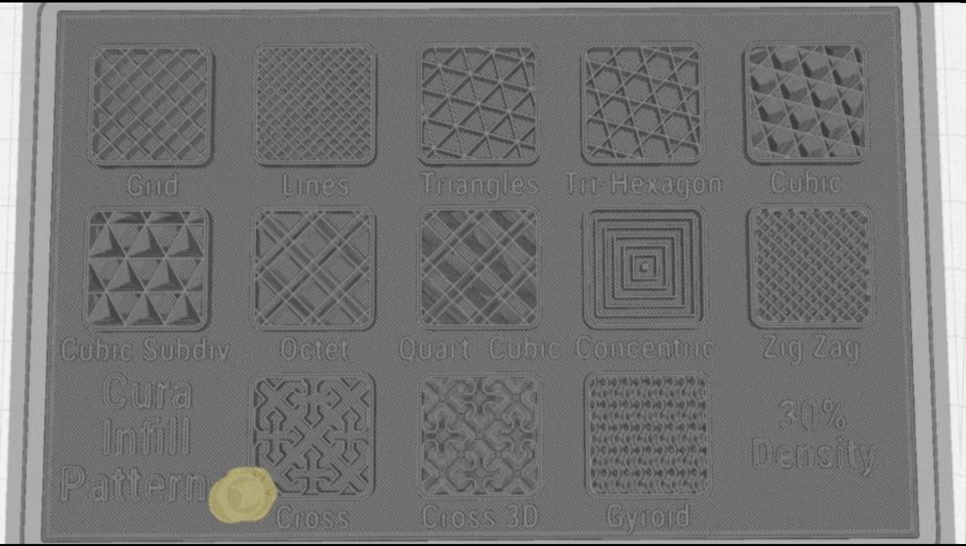
The algorithms attempt to optimize accuracy, quality, build time and material use.

https://formlabs.com/blog/topology-optimization/

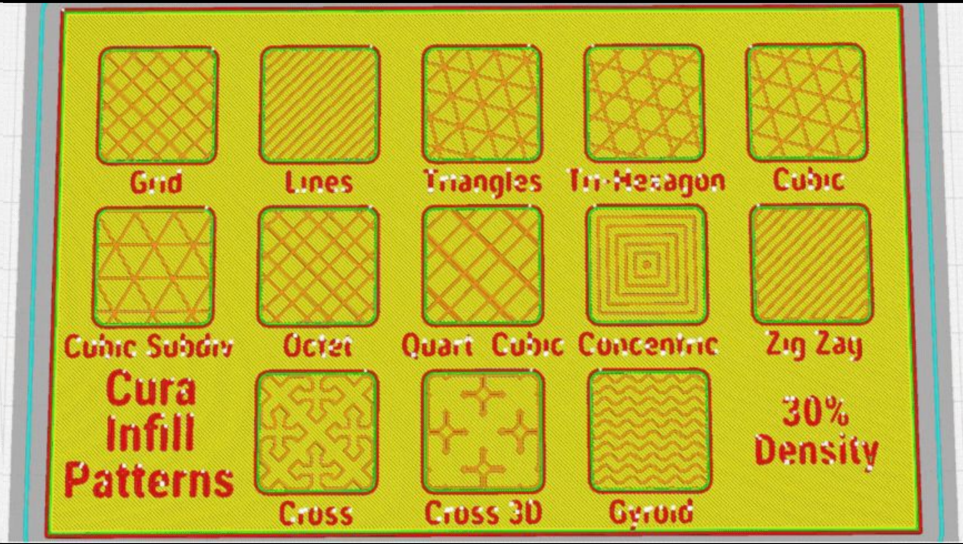
3dprint.com

3D Printing Algorithms

Infill Tool Path



Infill Layers



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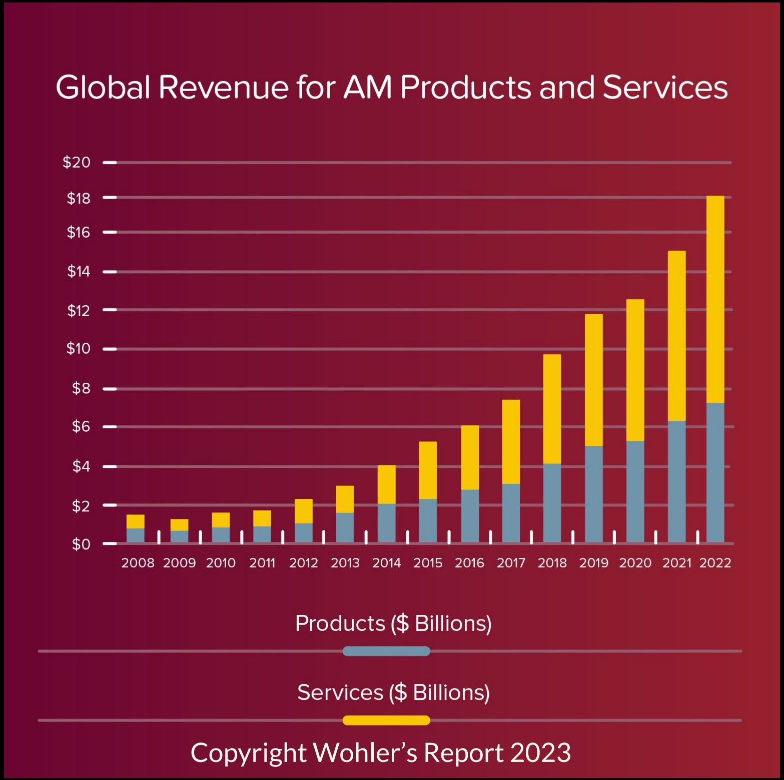
Additive Manufacturing Applications

Additive Manufacturing Applications



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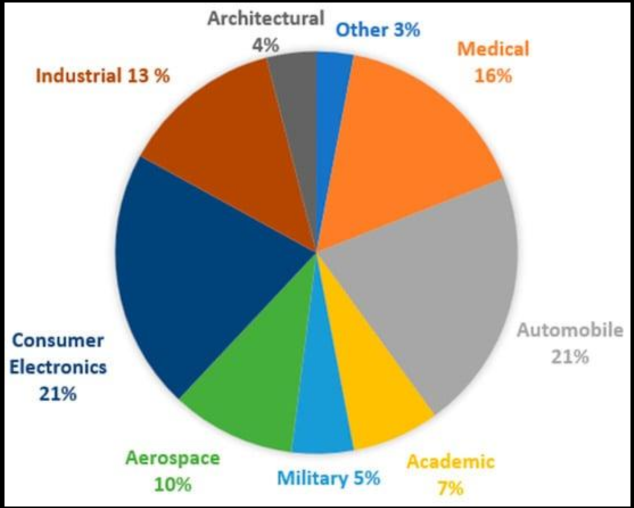
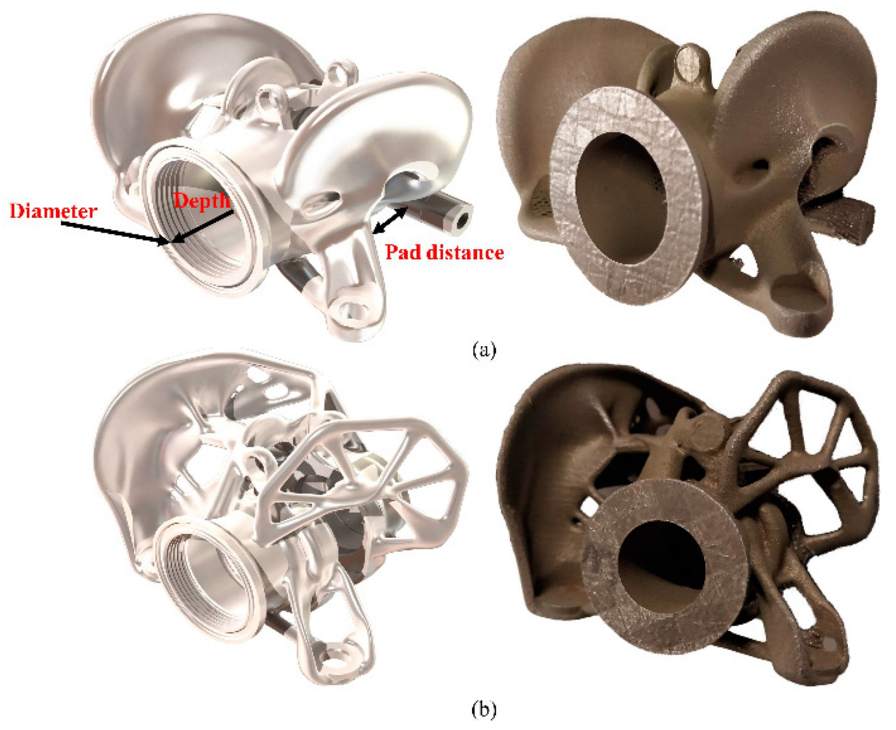


https://doi.org/10.3390/met14020195

https://doi.org/10.3390/polym15112519

Automotive Manufacturing Applications

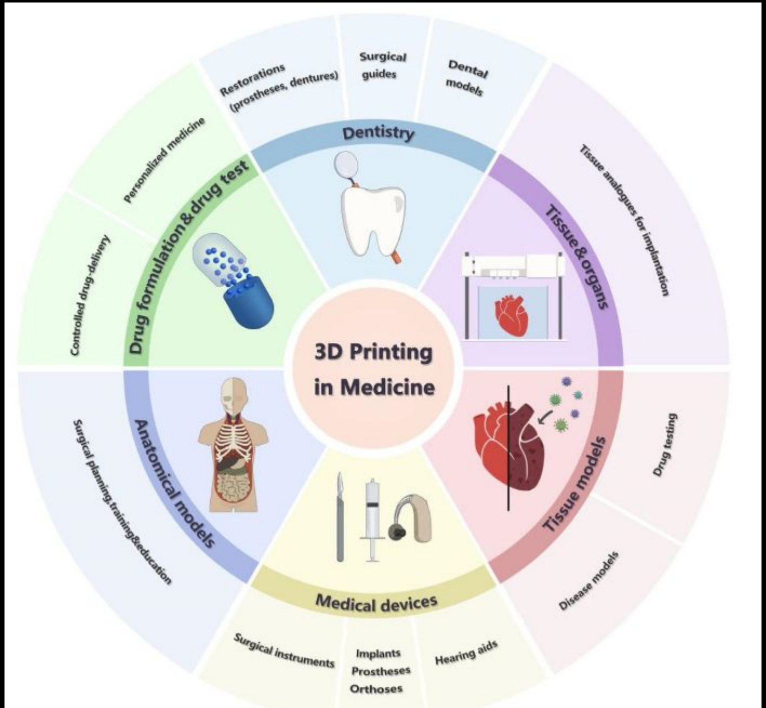
- Used a lot for prototyping and tooling, but is also used in actual manufacturing of parts
  - Combustion engine, electric motor, and drivetrain components
  - And many more!
- Unimplemented parts:
  - Topologically optimized brake calipers: 41% lighter than standard calipers



https://doi.org/10.3390/app11041437

Healthcare Applications

- ★ **Prosthetics and medical implants**
  - ○ Topologically optimized hip implants
- ★ **Bioprinting**
  - ○ Printing fully functional organs: not yet possible, but soon
  - ○ HEART project: Health Enabling Advancements through Regenerative Tissue Printing
    - ■ Stanford University research team received $26.3 million grant on September 23, 2023
    - ■ 5 year goal: print a fully functioning human heart in just one hour and transplant it into a pig



https://pubs.rsc.org/en/content/articlelanding/2024/bm/d3bm01934a

Sustainability

★ Decreases carbon emissions and waste material

★ CO2 emission are largely impacted by:

  ○ Type of energy source

    ■ kg of CO2 created per kWh of energy generated

  ○ Buy-to-fly ratio

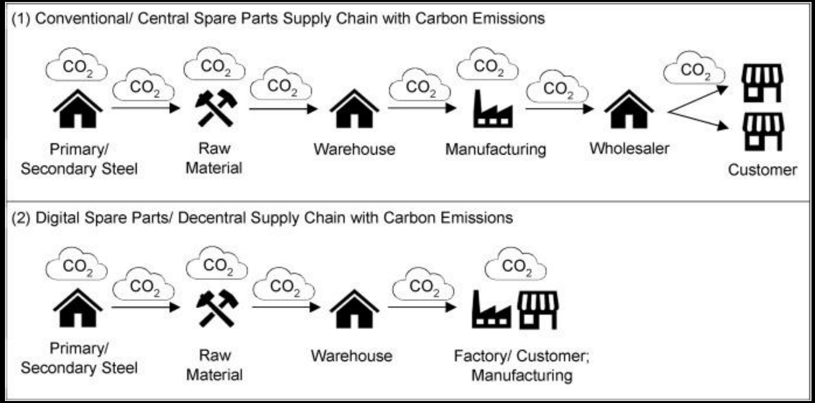
    ■ “the ratio of the weight of the raw material to the weight of the end product” (Rupp et al. 2022)

★ Digital spare parts: only print what you need, on-site production

  ○ Most effective for parts with a short manufacturing time and low, fluctuating demand

  ○ High investment costs, slow quality control, slow building speed

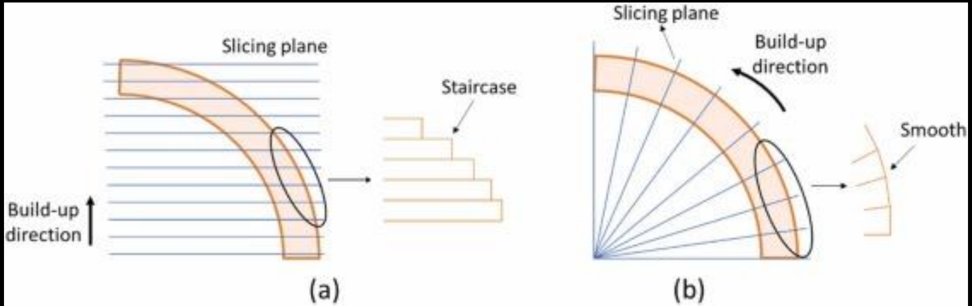
  ○ Requires a large amount of knowledge about additive manufacturing



https://doi.org/10.1016/j.cesys.2021.100069

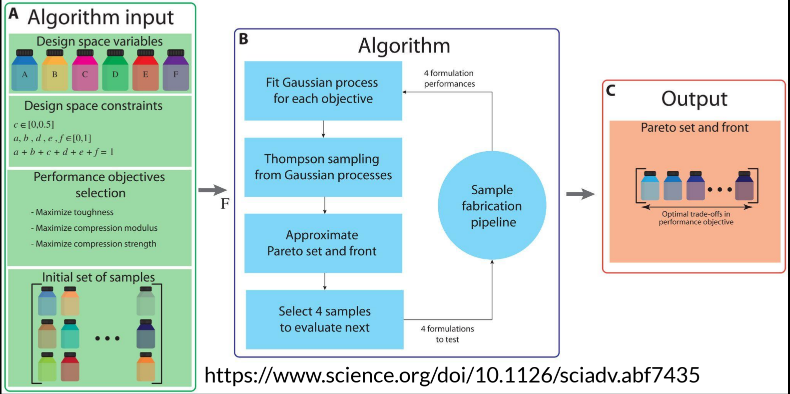
Emerging Techniques/Recent Advancements

New Algorithms



https://doi.org/10.1016/j.addma.2022.102622

- ★ New, dynamic multi-directional slicing algorithm
  - Reduces staircase effect and creates smooth finished surfaces
  - Can print overhangs without supports
  - Not great at multi-branches, could still be further refined

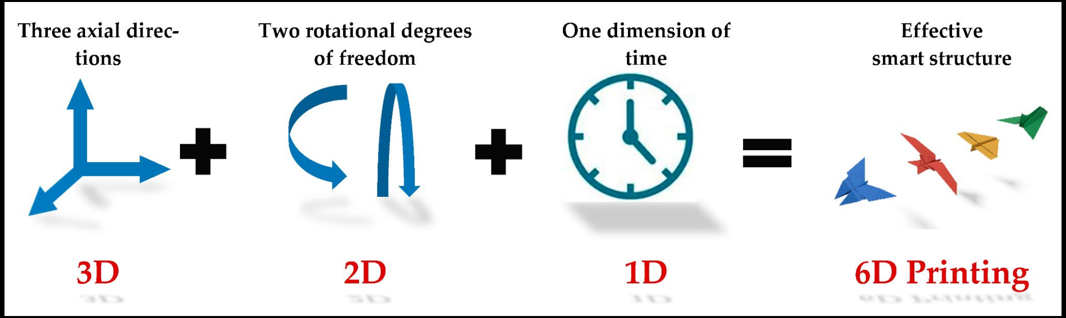


https://www.science.org/doi/10.1126/sciadv.abf7435

- ★ Finding new materials via algorithms
  - Finds new materials for 3D printing that are optimized for multiple objectives
  - Semi-automated, but a fully automated system is possible

So Many Dimensions: 4D, 5D and 6D printing

- 4D printing
  - Smart materials that change in response to a specific stimulus
    - **Materials:** shape memory alloys, shape memory polymers, and more
- 5D printing
  - Print bed rocks back and forth, adding two more axes and creating curved layers



https://doi.org/10.3390/jcs5050119

- 6D printing
  - Combines 4D and 5D printing to make better 4D smart products

Artificial Neural Networks and Additive Manufacturing

- Predict qualities of the final product
  - **SLS:** input parameters such as laser power, scanning speed, and powder layer thickness can be used to calculate the output parameters of density, part porosity, tensile strength, shrinkage percentage, and more of the final product
- Process Monitoring
  - By visual, *sound*, and other criteria
    - Sound is 83-89% accurate about the final quality of a product
    - There are more visual methods, and they vary more in accuracy
- Design feature recommendation
  - Assists new designers, spend fewer iterations, and less time and materials testing designs
- And more!

Conclusion

Conclusion

- 3D printing is the process of joining materials together to make something, usually layer by layer. There are a large variety of techniques and materials that can be used.
    - The most common technique is fused deposition modeling. Stereolithography and sintering techniques are also popular.
- 3D model data from CAD or 3D modeling programs is “sliced” into layers.
    - The topology and toolpath algorithms attempt to optimize accuracy, quality, build time and material use.
- Additive manufacturing has come a long way, but still has a long way to go!
    - We’re still a few years off from things such as bioprinting entire complex organs, but 3D printing is currently capable of *amazing* things in a large variety of fields.

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