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UNIVERSITÄTSMEDIZIN MANNHEIM

Medizinische Fakultät Mannheim der Universität Heidelberg
Universitätsklinikum Mannheim

Biomedical Engineering
3D Printing

Alena-Kathrin Golla née Schnurr

Schedule

Day	Date	Time	Lecturer	Topic
Tuesday	03.11.2020	13:00-14:30	Licht	Biosensors & Physiological Signals I
Tuesday	10.11.2020	13:00-14:30	Licht	Biosensors & Physiological Signals II
Thursday	12.11.2020	13:00-14:30	Tönnes	Bioelectrical Signals: EEG & ECG
Tuesday	17.11.2020	13:00-14:30	Reichert	Medical Imaging: MRI
Thursday	19.11.2020	13:00-14:30	Tönnes	Medical Imaging: CT, Xray & US
Tuesday	24.11.2020	13:00-14:30	Golla	Medical Imaging: Other
Thursday	26.11.2020	13:00-14:30	Andoh	Blood Flow & Pressure I
Tuesday	01.12.2020	13:00-14:30	Andoh	Blood Flow & Pressure II
Thursday	03.12.2020	13:00-14:30	Golla	Machine Learning I
Tuesday	08.12.2020	13:00-14:30	Golla	Machine Learning II
Thursday	10.12.2020	13:00-14:30	Golla	3D Printing
Tuesday	22.12.2020	13:00-14:30	All	Recap - Exam Preparations
Tuesday	26.01.2021	10:00-12:00	Golla, Tönnes	Exam
Wednesday	03.02.2021	08:30-10:00	Golla, Tönnes	Repeat Exam

Materials

Slides are available from our website:
https://www.umm.uni-heidelberg.de/inst/cbtm/ckm/lehre/

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Definition: What is 3D printing?

Also called additive manufacturing

creation of a physical object

from a three-dimensional digital model

usually done by laying down many thin layers of a material

Subtractive vs. Additive Manufacturing

Subtractive: excess material is removed	**Additive: fuses layers of material**
• Part quality and finish • Strength of part • More material choices • High precision • Cost effective for large part runs • Best for simple repetitive designs	• On demand with quick turn around • Customization of part • More complex and unique designs • Good for prototyping where multiple iterations are needed • Best choice for single or small batches of parts

3D Printing is old

- 1971: Johannes F Gottwald patented the Liquid Metal Recorder
- 1980/1: Hideo Kodama invents and patents photo-polymer method
- 1984: Charles Hull invents stereolithography (SLA)
- 1991 Stratasys produces first fused deposition modelling (FDM) machine
- 1999 Scientists implant grown organs and use 3d prints as support
- 2008 First person with 3D printed prosthetic leg
- 2009 DIY Kits for 3D Printers on the market

3D printing is not one single technology
- 7 Categories (ISO/ASTM International Standard):

1. **Material Extrusion** e.g. Fused Deposition Modelling (FDM)
   liquid material is deposited, which solidifies
2. **Vat Photopolymerizaition**, e.g. Stereolithography (SLA)
   liquid photopolymer is solidified by light
3. **Binder Jetting**
   an adhesive is deposited on layers of material (powder)
4. **Material Jetting**
   the print material is deposited and light-hardened

3D printing is not one single technology - 7 Categories (ISO/ASTM International Standard):

5. **Powder Bed Fusion** e.g. Selective Laser Sintering (SLS)
   layers of powdered material are sintered or melted together

6. **Direct Energy Deposition**
   simultanious material extrusion and energy/heat supply

7. **Sheet Lamination**
   Materialsheets (paper, plastic, etc.) are stacked and cut to shape

Abundance of available materials

ABS

Nylon

Epoxy Resins

PLA

Photopolymers

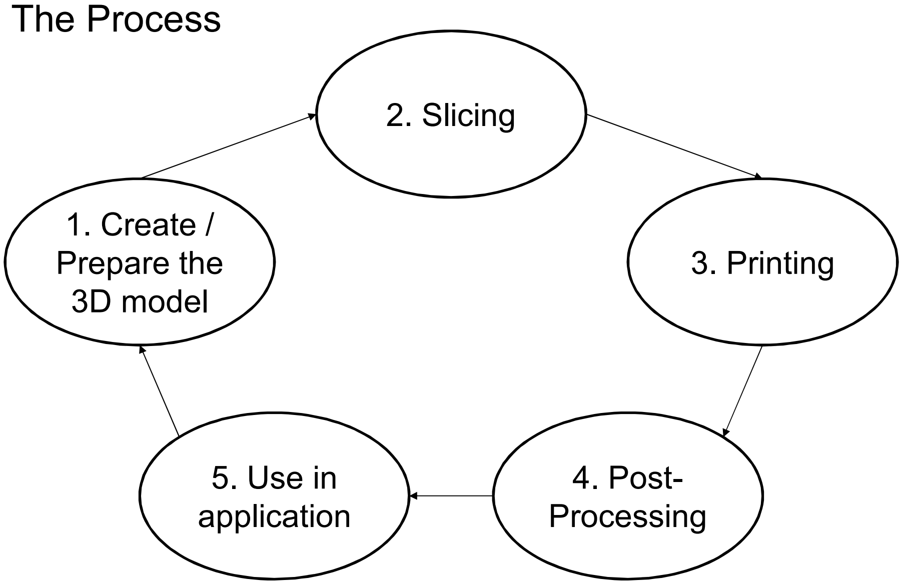
Steel

Wood

Titanium

Rubber

The Process



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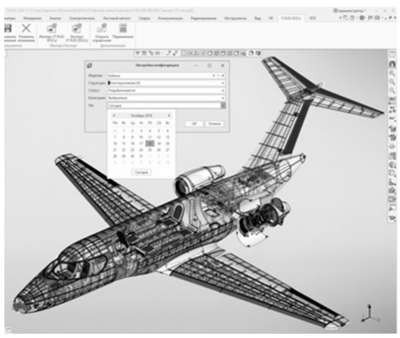
1. Create / Prepare the 3D model

- Design object in CAD or Modeling software
- Use 3D scans of objects
- Use a combination of both

- Objects need to have a clear inside and outside:
  - Watertight: No holes
  - No Disconnected elements
  - No zero width components



From https://commons.wikimedia.org/wiki/File:T-FLEX-CAD.png

- Standard file type: STL
- **ST**ereo**L**ithographie, referring to it’s initial use cases

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1. Create / Prepare the 3D model

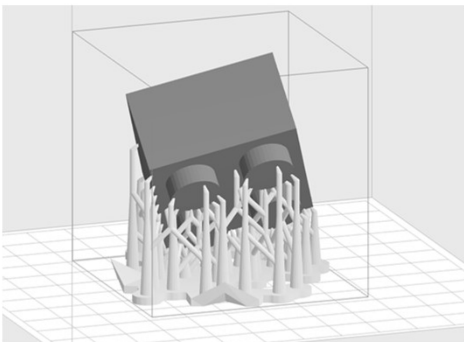
Also keep in mind:

- Limitation of printer:
  - Size, Resolution, Tolerances
- Depending on Technology:
  - Support
  - Escape Holes
  - cross-sectional area
- Material Strength:
  - Simulations
- Splitting the model may be required
- Add to material width to get correct dimensions after post processing

1. Create / Prepare the 3D model

Support

- Printers can't print on air.
- As a rule of thumb, overhangs with an angle <45° require additional support structures.
- E.g. a T shape could not be printed.
- Some methods can do bridges as in the H shape, which are supported by the columns left and right.



From https://commons.wikimedia.org/wiki/File:Supports_in_3D_printing.png

1. Create / Prepare the 3D model

Escape Holes

- Some technologies print in such a way that the print is emerged in the printing material.
- To empty hollow printed parts, an escape hole needs to be included in the design.

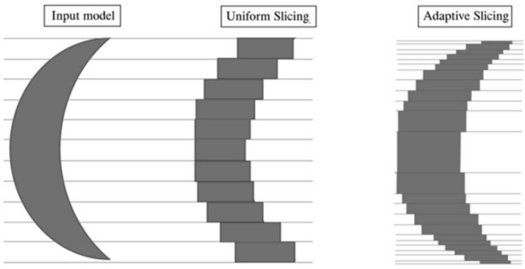
Cross-sectional Area

- For Stereolithographie methods, the cross sectional area along x-y axis has to be reduced
- otherwise print failure due to high separation force

2. Slicing

- Creates actual code for the printer
- Most methods create objects layer by layer.
- The object is “sliced” to generate toolpaths.

- Some technologies allow for varying layer height.
  This reduces artifacts in sloped regions.

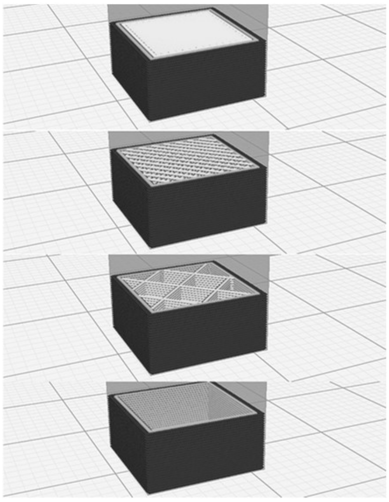


From https://commons.wikimedia.org/wiki/File:Adaptive_slicing_(1).png

2. Slicing

Before Slicing
- Keep Orientation in mind:
  - reduce support
  - ansiotropic material strength: prints are often stronger along x-y axis (layer direction) due to layer adhesion

Infill:
- Parts should often not be printed solid.
- They rather have a supporting structure inside, that has reduced density but gives high strength.



From https://en.wikipedia.org/wiki/File:Infill_density.jpg

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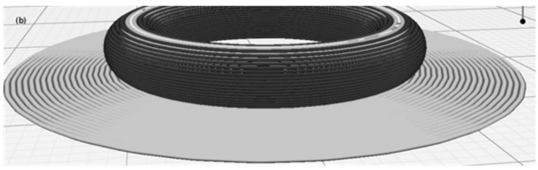
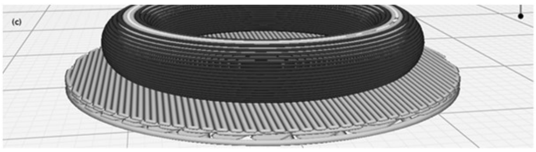
2. Slicing

For some technologies: Rafts/Brims improve bed adhesion
- Brim: Additional area on contact surface



- Rafts: Structure added under the object



These are exemplary: Different technologies - different considerations

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From https://commons.wikimedia.org/wiki/File:Skirts,_Brims,_Rafts.jpg

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4. Post-Processing

- Support removal
  - Support structures may be connected to the print.
  - Removing them leaves imperfections on the surface, which have to be corrected

- (Wet-) Sanding & Polishing
  - Removes layering artifacts / part connections, but difficult for complex shapes

- Painting
  - Only some methods allow for full color printing.
  - To achieve required optical results, need to be painted.
  - Unsuitable for mechanical parts.

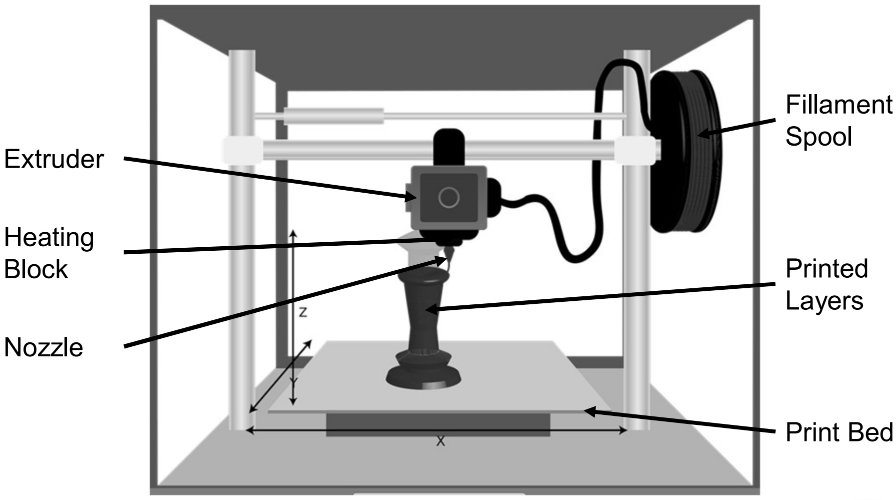
4. Post-Processing

- Chemical Smoothing
  - Some materials enable chemical surface smoothing, where smooth surface finish can be achieved.
  - This tends to smooth out details.

- Epoxy Coating / Metal plating
  - 3D printed plastic parts may be coated/plated to increase mechanical strength.

- Residue Removal
  - Some techniques have the printed object immersed in residues of printing material.
  - The removal of the residue can require some effort.

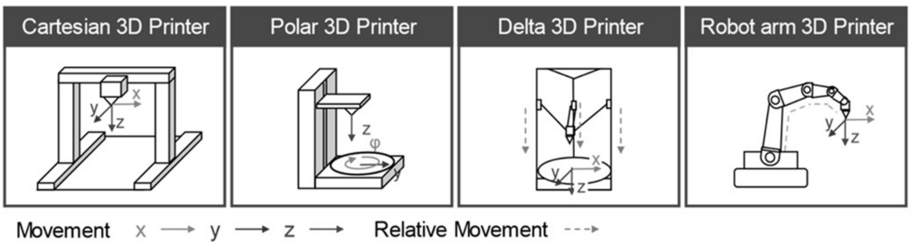
Fused Deposition Modeling (FDM) / Fused Filament Fabrication (FFF)



From https://pixabay.com/vectors/printer-3d-printer-model-3d-1248284/

Fused Deposition Modeling (FDM) / Fused Filament Fabrication (FFF)

Many printer designs exist



From Kampker, Achim & Triebs, Johannes & Kawollek, Sebastian & Ayvaz, Peter & Hohenstein, Steffen. (2019). Review on Machine Designs of Material Extrusion based Additive Manufacturing (AM) Systems - Status-Quo and Potential Analysis for Future AM Systems. Procedia CIRP

Fused Deposition Modeling (FDM) / Fused Filament Fabrication (FFF)

Advantages

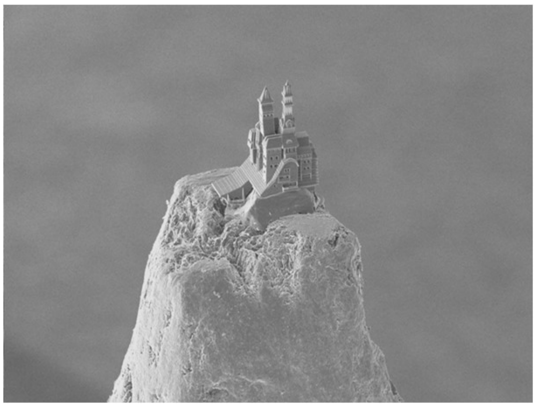
- inexpensive
- allows multiple materials
- relatively harmless (office ready)
- good structural properties
- wide range of resolutions/volumes possible

Disadvantages

- highly detailed models hard to achieve
- resolutions increases print time
- requires support material

Vat Photopolymerization

- Starts with a basin filled with photopolymer
- Transitions from liquid to solid with certain light
- Isotropic prints because layers bond chemically
- Objects need to be drained afterward and resin washed off
- Variants exist which allow for microscopic details!

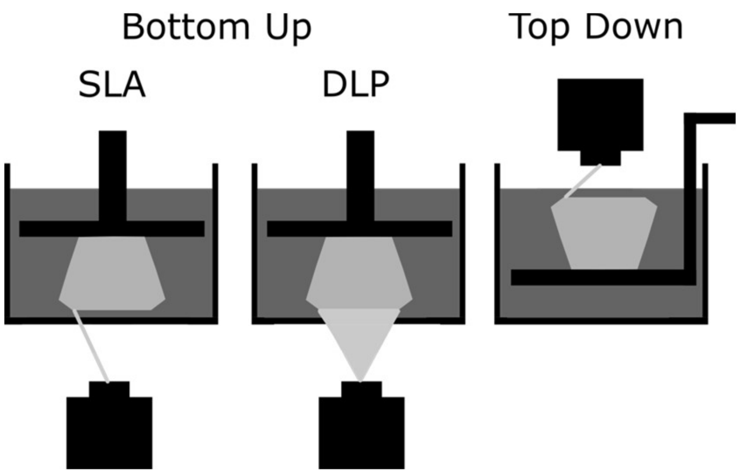


Multiphoton lithography: castle on pencil tip

From https://commons.wikimedia.org/wiki/File:Burg_auf_einer_Bleistiftspitze.tif

Vat Photopolymerization

SLA - Stereolithographie
DLP - Digital Light Processing



Vat Photopolymerization

Advantages

- High resolution
- Good surface finish
- Fast, espacially DLP

Disadvantages

- Often more fragile
- Use of chemicals
- Requires support
- Lengthy Postprocessing
- Limited Materials

Break

Do you have any questions so far?

Binder Jetting

- a binder is applied onto powder material
- This makes even temperature sensitive materials printable
- A variety of binders is usable, even on the same print:
  - several material properties achievable in the same print
- common post-processing steps:
  - Curing, sintering, additional finishing are steps
- Binder may eject powder from surface, leading to imperfections

Binder Jetting

Advantages

- fast printing process
- versatile materials
- no support needed

Disadvantages

- unfinished surface inherent
- time consuming postprocessing
- low strength

Material Jetting

- Closest relation to “regular” printing
- The printing material is directly ejected from with inkjets
- Uses multiple printheads for multiple materials (print / support)
- Commonly uses photopolymers as material,

  which is hardened each layer

Material Jetting

Advantages

- high resolution
- smooth surfaces
- easily multi-material

Disadvantages

- poor mechanical properties
- expensive
- high support usage

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Selective Laser Sintering (SLS)

- Layer of powder is deposited
- Laser traces shape, to fuse the powder layers together
- Process is repeated until entire shape printed
- No support structures needed, as powder acts as support!
- Materials range: plastics, metals, ceramics, glass

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Selective Laser Sintering (SLS)

Advantages

- powder bed is self-supporting
- 3D nesting of multiple parts
- high part strength
- high chemical resistance
- material variety
- fast

Disadvantages

- porous surfaces
- expensive
- wasted powder

Electron Beam Melting (EBM)

- Instead of laser, an electron beam is applied
- Relies on electron uptake, so only used for metals
- Requires vacuum chamber, to prevent oxidation of metal powder
- Melting achieves more homogenous material properties than sintering
- Separation of electron beam allows heating of area simultaneously

Electron Beam Melting (EBM)

Advantages

- High strength of parts
- Faster than laser sintering
- Few supports, if any, needed

Disadvantages

- Lower accuracy due to grainsize
- Only metals
- Limited build volume
- Expensive

Direct Energy Deposition

- Material and Energy are deposited simultaneously
- Material is either powder or wire, mostly metal is used
- Energy supply in form of laser-, electron beam or plasma/electric arc
- Unique: Allows for the repair of damaged parts
- Requires hermetically sealed chamber to stop oxidization of material

Direct Energy Deposition

Advantages

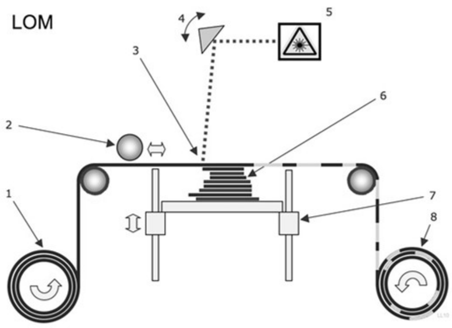
- fast
- strong parts
- minimal post processing
- applicable for repairs
- large volume

Disadvantages

- high cost
- low resolution
- no supports possible, so no overhangs

Sheet Lamination (example: LOM)

- A heated roller (2) presses the sheet (1) with adhesive against previous layers(6).
- The laser (5 & 3) is redirected with a prism (4) to trace the object.
- Outside parts are cross hatched for removal.
- The platform (7) is lowered to make space for next layer.
- The remaining material is kept on a roll (8).



From https://en.wikipedia.org/wiki/Laminated_object_manufacturing#/media/File:Laminated_object_manufacturing.png

Sheet Lamination

Advantages

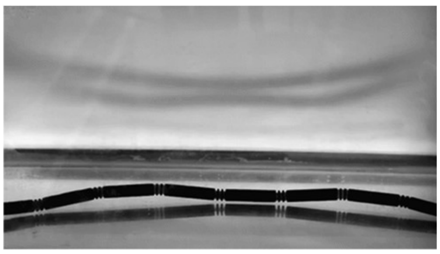
- Low cost due to material (paper, plastic, metal,...)
- allow full color prints
- fast
- large prints easily possible

Disadvantages

- layer height fixed by sheets
- limited materials
- waste & waste removal
- layer bonding strength limited

Outlook: 4D Printing

- Term describing prints that change shape after stimulation
- Techniques commonly based on (proj. micro) SLA
- Based on precise single or multi-material prints
- Activation based on photons, heat, chemical,...
- In early stages, but with huge potential



From Matthew Young - https://all3dp.com/4d-printing/

Applications in Medicine

- At an increasing rate, printing methods become adapted for medical usages.
- Multiple applications are already being explored:
  - Developement of surgical tools,
  - operation planning,
  - orthopedic implants,
  - prosthetics,
  - replicas of organs

Applications in Medicine

- Fast production enables patient specific tools.
- Printing customized parts is supported by modern imaging methods such as CT and MRI, which enable the construction of digital 3D models of the patients.
- For visible organs, laser scanners and other optical methods can be used.
- Typical advantages are also important here:
  Fast iterations with fast feedback with relatively low cost.

Applications in Medicine

Customized Tools:
- Materials and procedures according to medical standards are used

Surgical guides:
- Custom shapes based on scand ensure tight fit and that tools are applied at correct position.

Surgical blades:
- Hipcup removal blades were produced with laser melting, reducing cost and decreasing rejection rate of hip implants

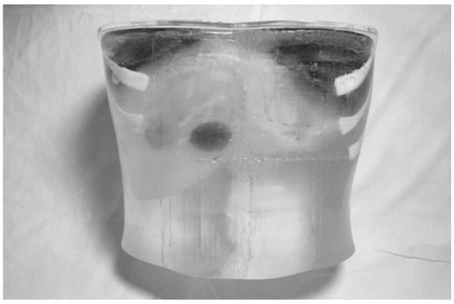
Also: Casts, handles, retractors, ….

Sterilization Methods

There are multiple sterilization methods available for printed parts, depending on the technology and material used:
- Autoclave
- ethylene oxide
- hydrogen peroxide
- gamma radiation
- gas plasma

Medical Phantoms

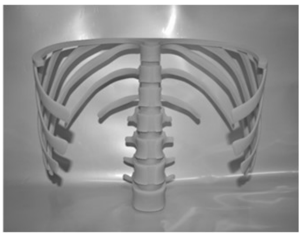
- Multimaterial printing enables mimicking even complex structures in terms of look and feel.
- Important for practice of surgery, preoperative planning, education and research.



M²OLIE Phantom

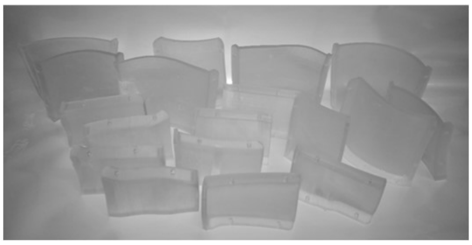
Medical Phantoms

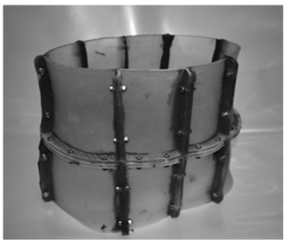
Liver Mold: SLA



Bones: SLS

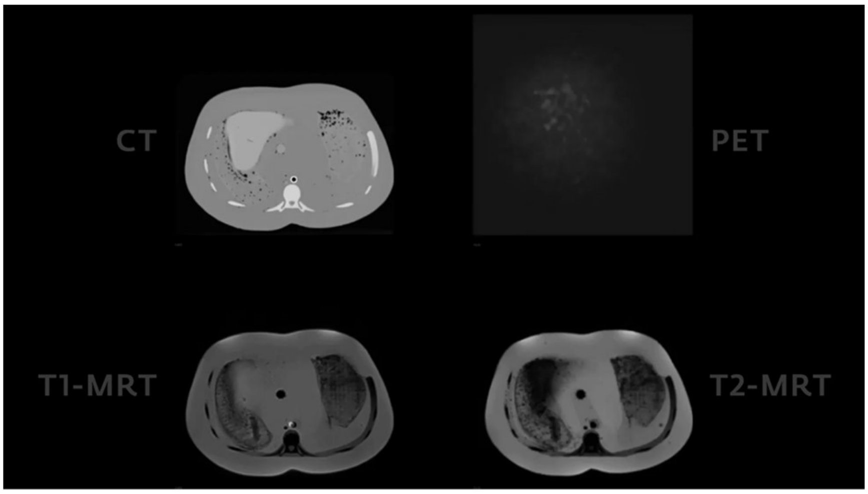
Lungs: FDM





Torso Hull: SLA

Medical Phantoms



Prosthetics

- 3D printers are used to build prosthetic hands, arms, feet and legs.
- Careful designs can reduce weight, while having the same strength.
- It enables not only cost reduction for custom parts,

  but also makes the construction of “designer” prosthetics easier.
- 3D printed prostheses are a cost-effective way to keep up with a child as they grow.
- most 3D printing plastics commercially available aren’t strong enough to support body weight

Orthopaedic implants

- Designs with fine porous surface allow for fast integration of living bone and implant, previously done by etching in post process.
- This reduces rejection rates.
- EBM and Selective Laser Melting are mainly used, to produce the metal implants.
- Their resolution allows for the direct production of porous patterns.

Pharmaceuticals

- There is research in creating drugs with customized release patterns, including time-programmed multi-drug pills.
- Examples are the printing of thermolabile ingredients and other pharmaceutical grade polymers.

Bioprinting

- Bioink: cells are mixed with a special liquefied material that provides oxygen and other nutrients to keep them alive
- Printing method:
  - Photolithography
  - magnetic bioprinting
  - Stereolithography
  - direct cell extrusion
- bioprinted pre-tissue is transferred to an incubator, where matures into a tissue.
- long-term goal: print an entire organ

Summary

- Definition and Categories of 3D Printing
- The Printing Process
  1. Create / Prepare the 3D model
  2. Slicing
  3. Printing
     - FDM, Vat Photopolymerization, SLS, EBM, Binder Jetting
     - Material Jetting, Sheet Lamination, Direct Energy Deposition
  4. Post-Processing
  5. Use in application
- Applications in Medicine