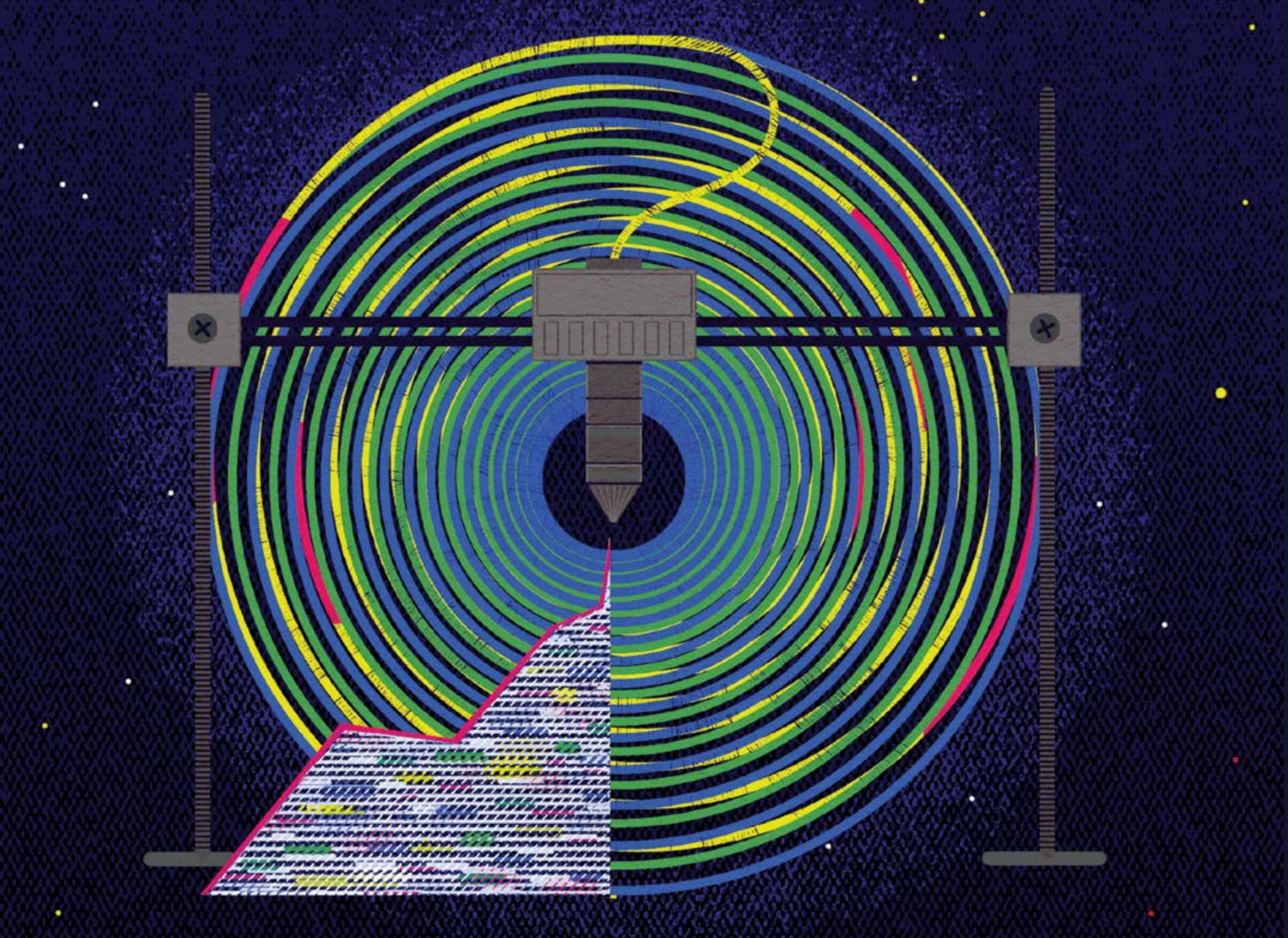


The Role of Ink Jet in Additive Manufacturing

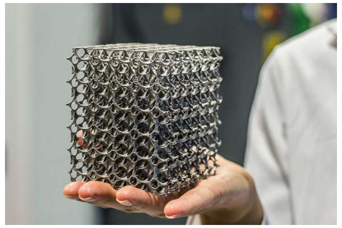
George A. Gibson
G² Tech Acceleration

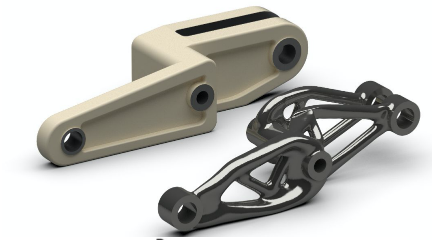
What we'll talk about today

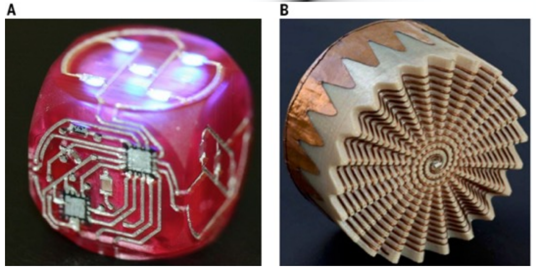
- Some operational definitions.
- Is this a big deal?
- The bestiary of AM – where does inkjet show up?
- What are the CTQ's?
- Material jetting
- Binderjet
- Multijet Fusion
- Composite Based Additive Manufacturing

So what is additive manufacturing anyway

- Additive Manufacturing - the technologies that build 3D objects by adding layer-upon-layer of material, whether the material is plastic, metal, ceramics, pharmaceuticals (and related components), concrete, biomaterials, metamaterials (4D printing?) or maybe one day…..human tissue.
- Many techniques can produce objects with more than one type of material
- The principal point of employing an additive manufacturing (AM) system is to fabricate parts with (nearly) arbitrary geometrical complexity and with relatively minimal tooling cost and time.
- Enable generative design – make form follow function unconstrained by the limitations of subtractive manufacturing techniques



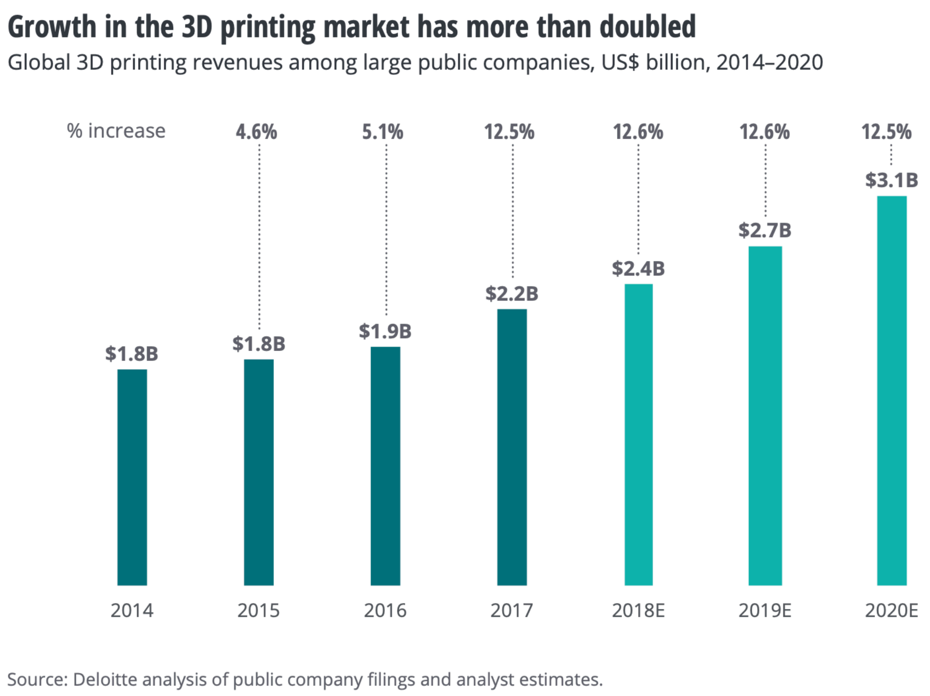




(A) A gaming die with an embedded processor and accelerometer. [From (7)] (B) A 3D periodic spiral antenna. [Draper Labs]

Is this a big deal?

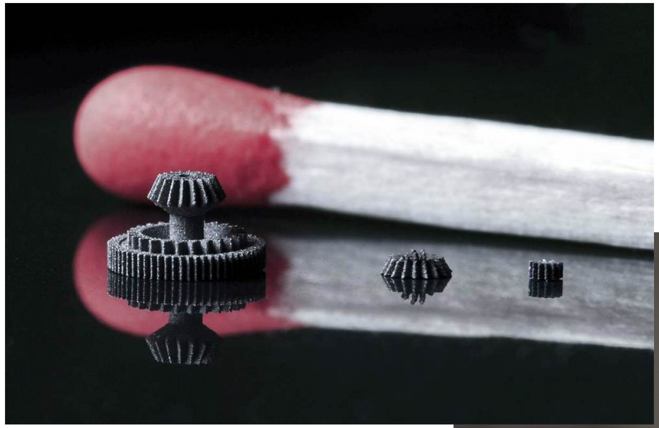
- Deloitte Global predicts sales related to 3D printing **by large public companies (**enterprise 3D printers, materials, and services) >$2.7B in 2019, >$3B in 2020
- Big but - global manufacturing sector ~$12T annually.
- Rhyming with digital print - first low volume and work process streamlining, then expanding in run length and using the distinctive digital attributes – viz – things that can't be made other ways.

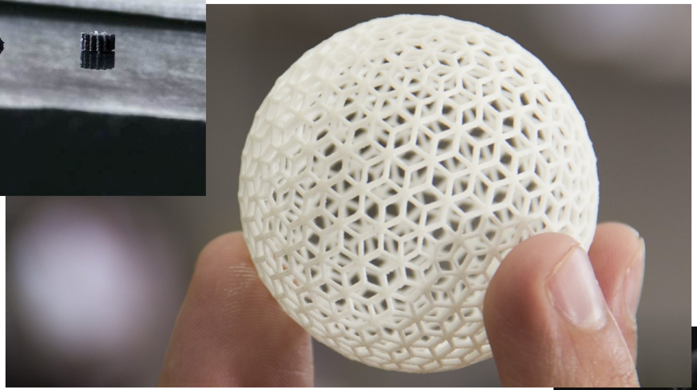


Is this a big deal?

And this is just the tip of the iceberg!
My personal directory has 176 companies and is continuing to grow

Is this a big deal?



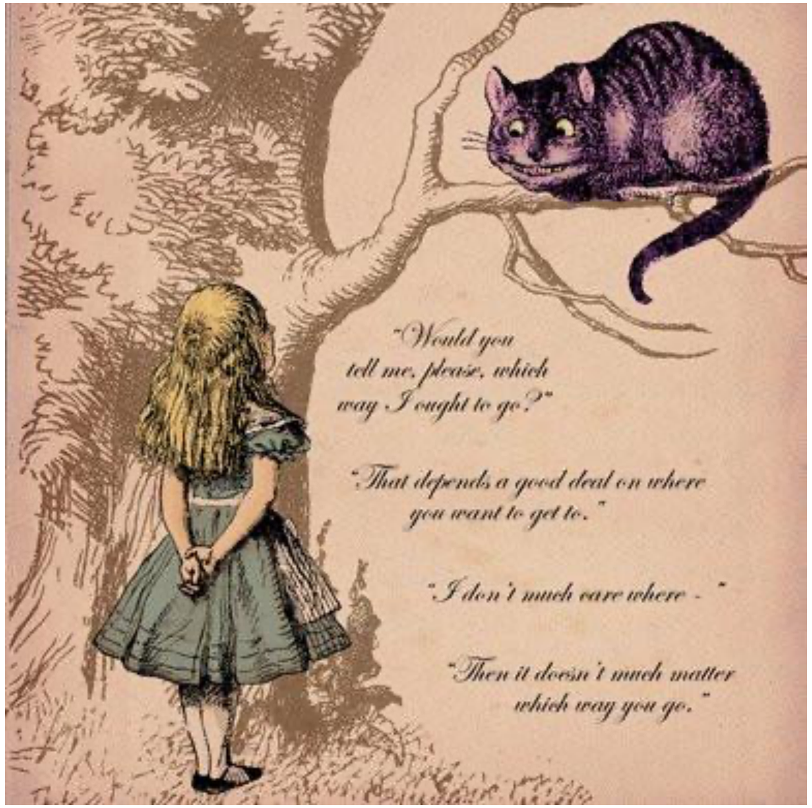


Is this a big deal?

What are the trends?

- Increasing number of firms (lots of venture funding, M&A on the way up)
- Increasing diversity of applications
- Increasing speed
  - 3D printers on the market in 2019 are ~2x as fast as those that were available in 2014
- Increasing build volume
  - A few years ago the big ones were 1l, now 27l is not uncommon – and on the high-end Oak Ridge National Laboratory with its Big Area Additive Manufacturing (BAAM) technology not to mention bridges and houses
- Increasing material choices
  - Number of materials that can be printed more than doubled in the last 5 years
  - Categories expanding including composites
- Increasing degree of automation
- Increasing sophistication of design and workflow management tools

Is there a "best" technique?



- No
- Application and even organization dependent
  - *Alice:* Which way should I go?
  - *Cat:* That depends on where you are going.
  - *Alice:* I don't know.
  - *Cat:* Then it doesn't matter which way you go.
- Results are about more than the printing technique
- Post processing – AM's dirty little secret
- Business process integration – it's not ***JUST*** a new way of making stuff
  - Digital Thread for Additive Manufacturing (DTAM)

Is there a “best” technique?

- Important considerations
  - How big are the parts you’re considering making?
  - What kind of application do you have in mind
    - Will it require production strength and durability?
    - Are you mainly going to make functional prototype where limited-use strength is OK?
    - Are appearance and surface finish important?
    - Will you be making sacrificial forms e.g. for investment casting?
  - What’s your target volume?
  - How important is turn around?
  - What sort of geometric accuracy and precision is required?
  - Do your applications require color or transparency?
  - What materials do you want to use?
  - How often do you expect to change materials?
  - How important is part cost?
  - How important is capital cost viz. what’s your budget for acquisition?

What qualifies as a strength?

- Speed
- Build volume
- Resolution
- Accuracy
- Range of materials
- Surface finish
- Ease of post processing
- Cost (capital and consumable)

What qualifies as a weakness?

- Low part strength compared with conventional materials (especially Z direction)
- Cost of hardware
- Cost of materials
- Time and effort to do post processing
- Inability to scale

Range of materials

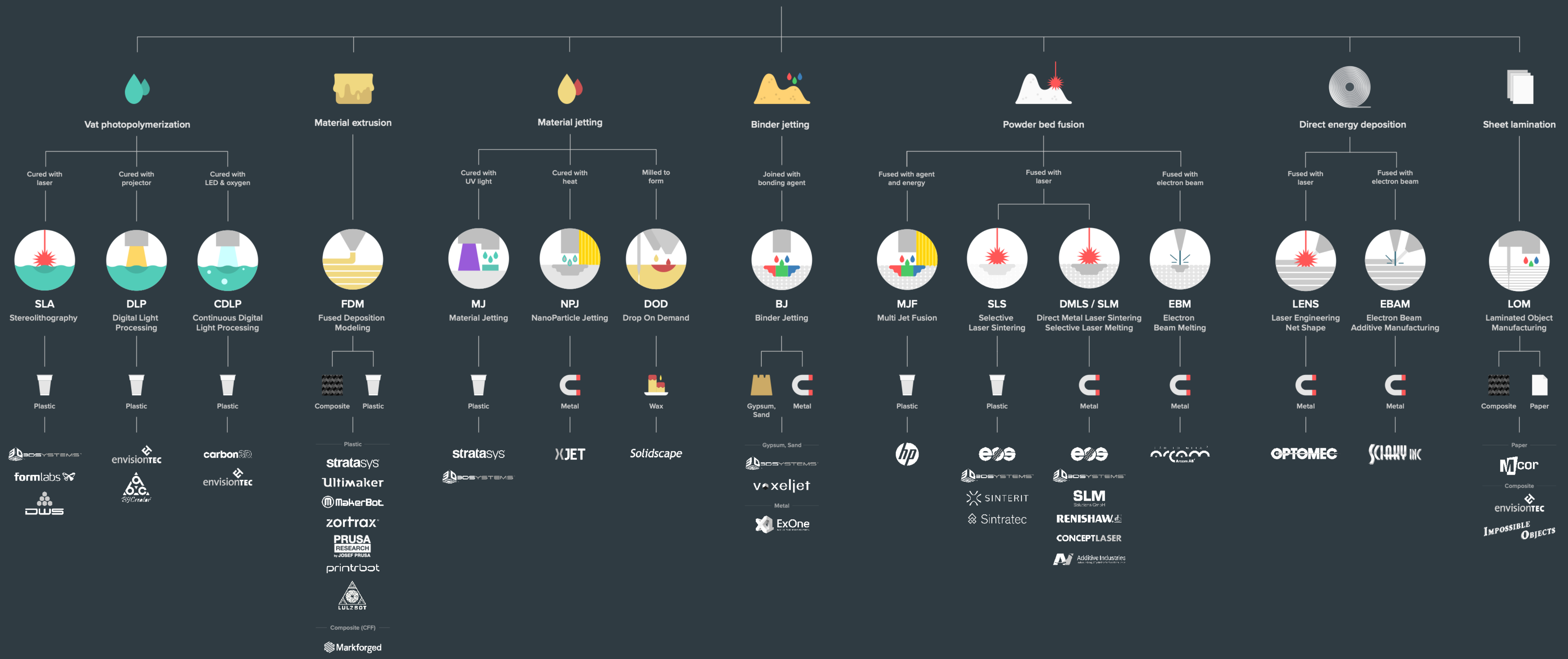
- Customers want materials that meet their application requirements
  - Mechanical properties tensile and flexural properties, impact resistance
  - Thermal properties glass transition temperature (Tg), MI
  - Electrical properties
  - Color
  - Low cost
  - Multi-source
  - …
- Suppliers want materials that keep their customers and their own boards happy
- As a result there are a large number of materials and a growing number of suppliers
- Most printers have captive materials

Surface finish

- Linked to resolution, precision and support
- Photochemical products generally are held to rule
- Driven by both aesthetics and functional requirements
  - E.g. with analog circuits operating at RF frequencies, very high-speed circuits, and antennas, rough conductors can lead to issues like frequency mixing at high intensity, signal reflections at rough spots along the surface, and difficulty with impedance control routing throughout a PCB.
- Drivers include layer thickness, support attachment/detachment, accuracy and precision
- Everybody is trying hard to get better
- How much hand polishing do you want to do?

Printer / Technology	Layer Thickness
Professional fused deposition modelling for production (Stratasys, etc.)	0.17 mm to 0.33 mm (0.007” to 0.013”)
Office or fablab fused deposition modelling (Makerbot, Ultimaker, etc.)	0.10 mm to 0.33 mm (0.004” to 0.013”)
Selective laser sintering (SLS) – (EOS, 3D System)	0.060mm to 0.150 mm
Material jetting (Stratasys Polyjet)	0.016mm to 0.028 mm
Material binding (3D Systems ZPrinter)	0.1 mm
Stereolithography, DLP, resin hardening by light	0.05 mm to 0.15 mm
Wax deposition by piezoelectric head (Solidscape)	0.005 mm to 0.10 mm

ADDITIVE MANUFACTURING TECHNOLOGIES



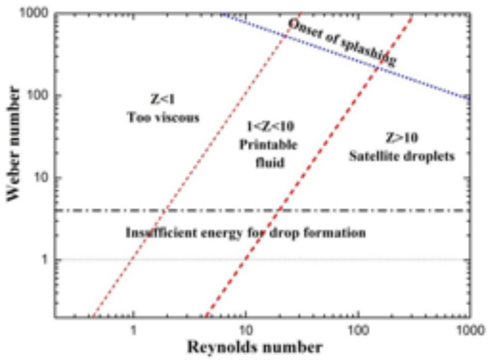
Every company and academic group is branding their own variant – that's unlikely to stop soon.

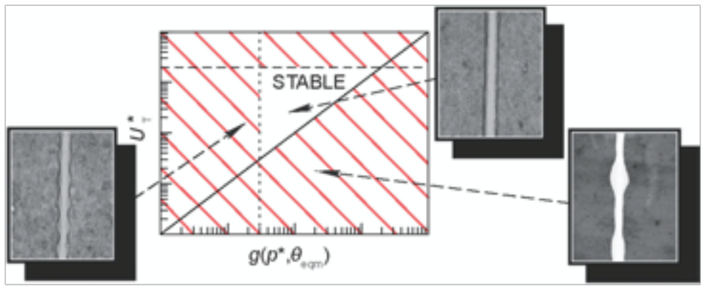
3D HUBS

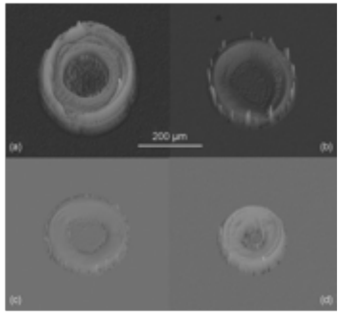
What we’ll talk about today

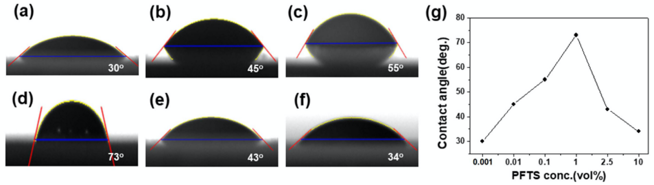
- Material jetting
    - Polyjet
- Powder bed-based techniques
    - Binder jet
    - Jet Fusion
- CBAM
- There are lots of others

Ink jetting for AM is still ink jetting









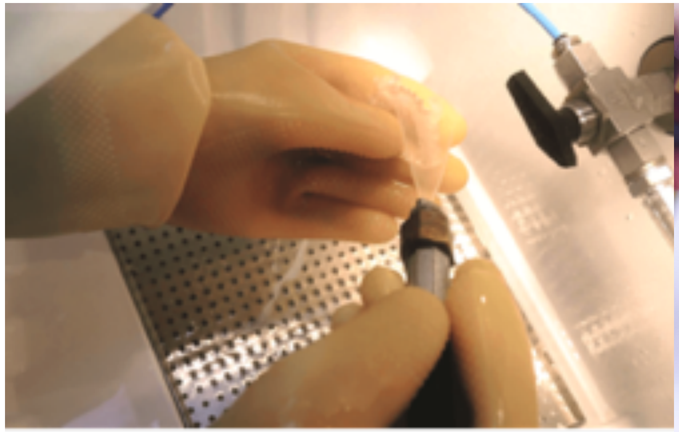
- None of the important things about jetting go away
- Differences among the IJ processes (e.g. direct material jetting v Jet Fusion)
- Wetting and spreading become more important in material jetting – Z strength – and interacts with cure
- Effect of particulate fillers

Supports

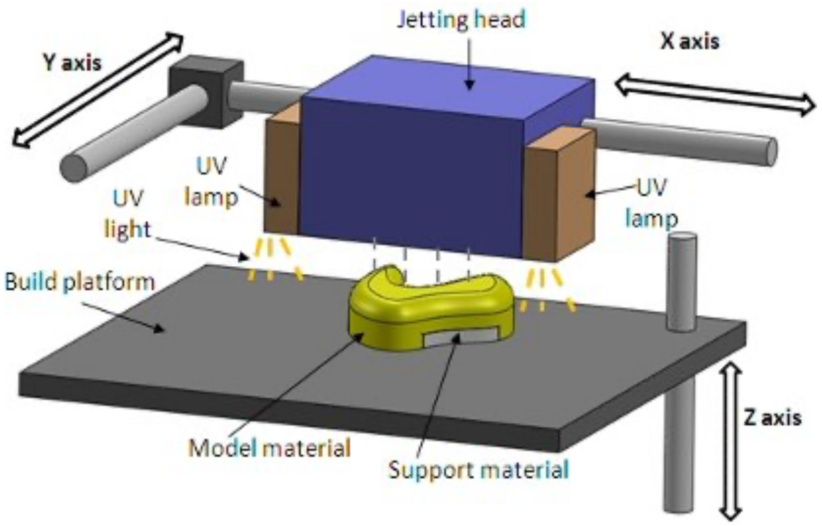
- A necessary evil for some processes
- Required for overhangs and bridges
- Prevents warpage and other distortions
- Material jetting – nearly always used
- Binder jet and Jet Fusion – never used but post processing still required
- CBAM never used but post processing still required

Support removal

- Shearing
- Dissolution
- Vapor or solvent smoothing
- Thermal
- Media blasting
- Hand polishing



Material Jetting



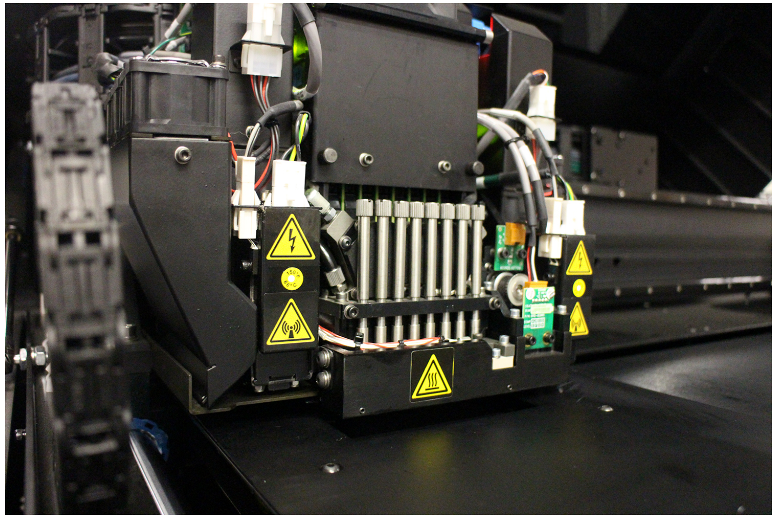
- Most commonly photopolymers or waxes
- Cures with UV or hardens on cooling
- Allows for multi-material printing
- Often uses soluble support material (aq. NaOH or water jet)
- High dimensional accuracy, high resolution and thin layer thickness frequently yields smooth surface finish
- Advantages:
  - The process benefits from a high accuracy of deposition of droplets and therefore low waste
  - The process allows for multiple material parts and colors under one process
- Disadvantages:
  - Support material is often required and therefore needs to be removed
  - A high accuracy can be achieved but materials are usually captive

Polyjet

- A representative device -Stratasys Objet260 Connex3
- Build volume ~13l
- Resolution: XY, 600 x 600 dpi; Z, 1600 dpi (16μ)
- Up to **82(!!)** materials per part
- Over 1,000 materials options

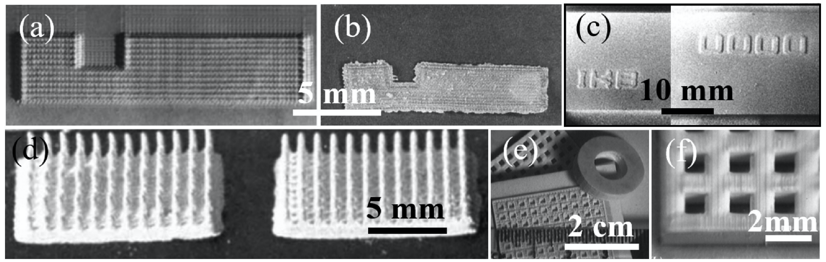


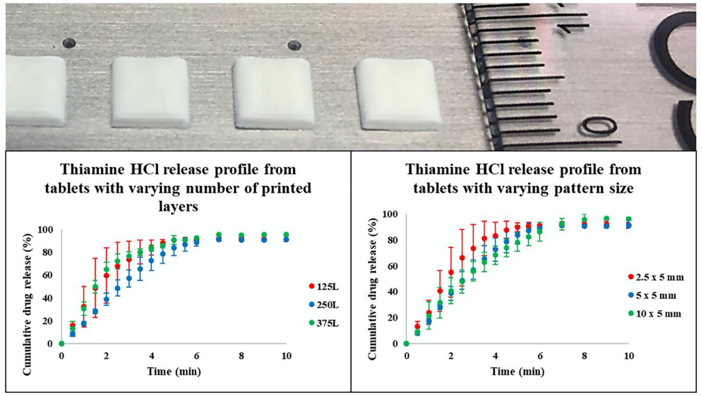


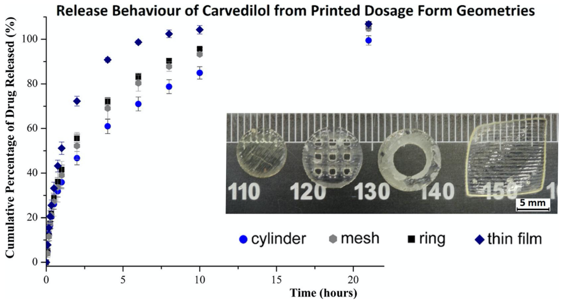


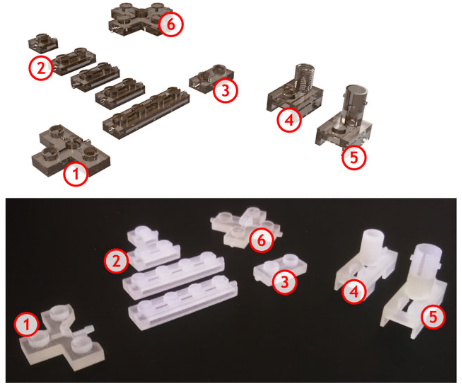
Material jetting

- Ceramics
  - Nanoparticle TiO_2, ZrO_2 and Al_2O_3 slurries (up to ~30%) have been successfully jetted and cured to yield green bodies, consolidated by sintering.
  - Too little inorganic leads to shrinkage and distortion during consolidation
- Drugs
  - Whole tablet printing from PVP and thiamine hydrochloride in an aq ink from a Fuji Dimatix head yielding an entire free-standing tablets without an edible substrate being part of the tablet.
  - UV curable 10 wt% carvedilol, Irgacure 2959, and a photocurable N-vinyl-2-pyrrolidone (NVP) and poly(ethylene glycol) diacrylate matrix. Over 80% release of the drug independent of shape.
- Biomaterials
  - Printed modular microfluidic chips for on-chip gel electrophoresis.



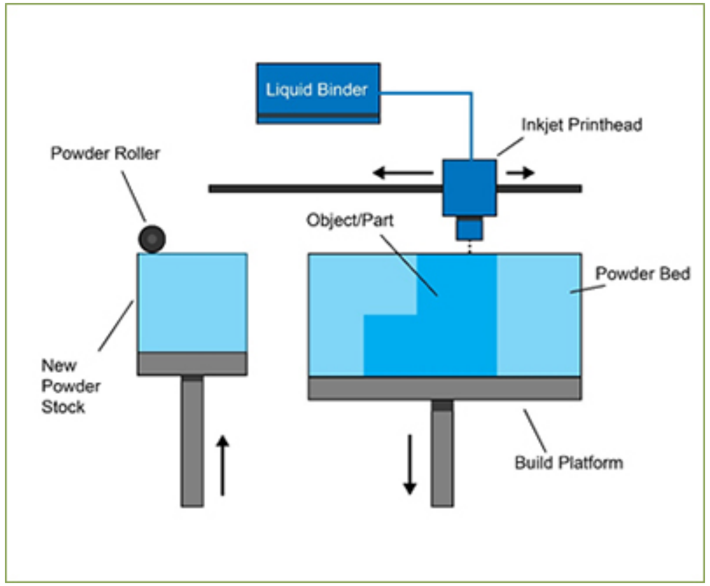






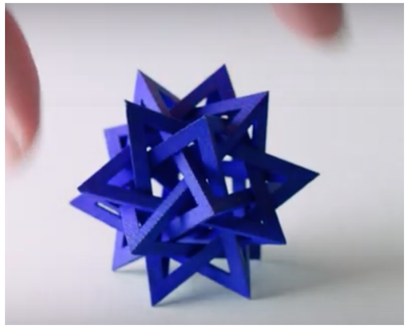
Binder Jetting

- A powder base material and a jetting fluid that serves as (or activates) the binder
- The growing object is self-supported within the powder bed
- Generally faster than material jetting
- Color
- Lots of material flexibility (polymers, ceramics, metals)
- Defects can arise from splattering when the drop hits the powder bed, powder bed depletion, ejection of partially bound agglomerates
- Heated build chamber often used – cooling profile & stress relief
- Object surfaces may be somewhat porous and have an "unfinished" surface
- Not always suitable for structural parts, sometimes, require further infiltration, sintering, or casting to be reinforced

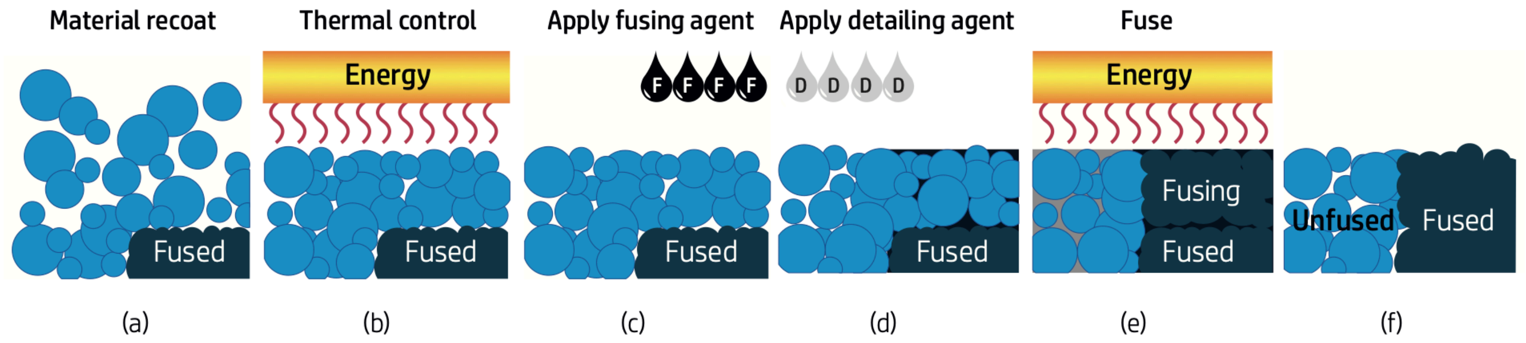


Binder jet variants: High Speed Sintering

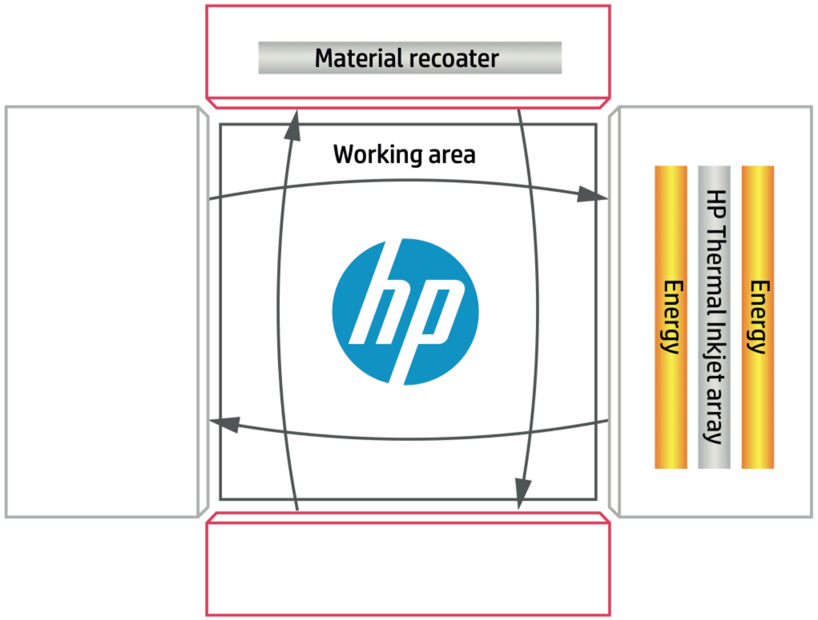
- The fluid printed is an ir absorber
- Each layer is irradiated, causing only the printed areas to melt/sinter
- Wide range of polymers from elastomers to engineering grade polyamides.
- Strength and stiffness are comparable to other polymer powder-based approaches while ductility (Elongation at Break) is often significantly higher.
- The process requires no support structure and features as small as 0.5 mm can be easily reproduced.



HP Multi Jet Fusion



- A powder bed approach
- Heated chamber
- 2 jetting fluids
- After job completion, the build unit is rolled into a Jet Fusion Processing Station for cooling, unpacking the parts, and recovery and refreshing the build unit.
- While those processes are completing, a build unit that has been refreshed by the processing station can be rolled back into the printer for continuous production.



HP Multi Jet Fusion

- Long cooling cycles – over 48 hours
- Post processing includes bead blasting
- A notable success case SmileDirectClub
- 49 HP 4210 printers
- 50,000 clear dental aligner molds per day

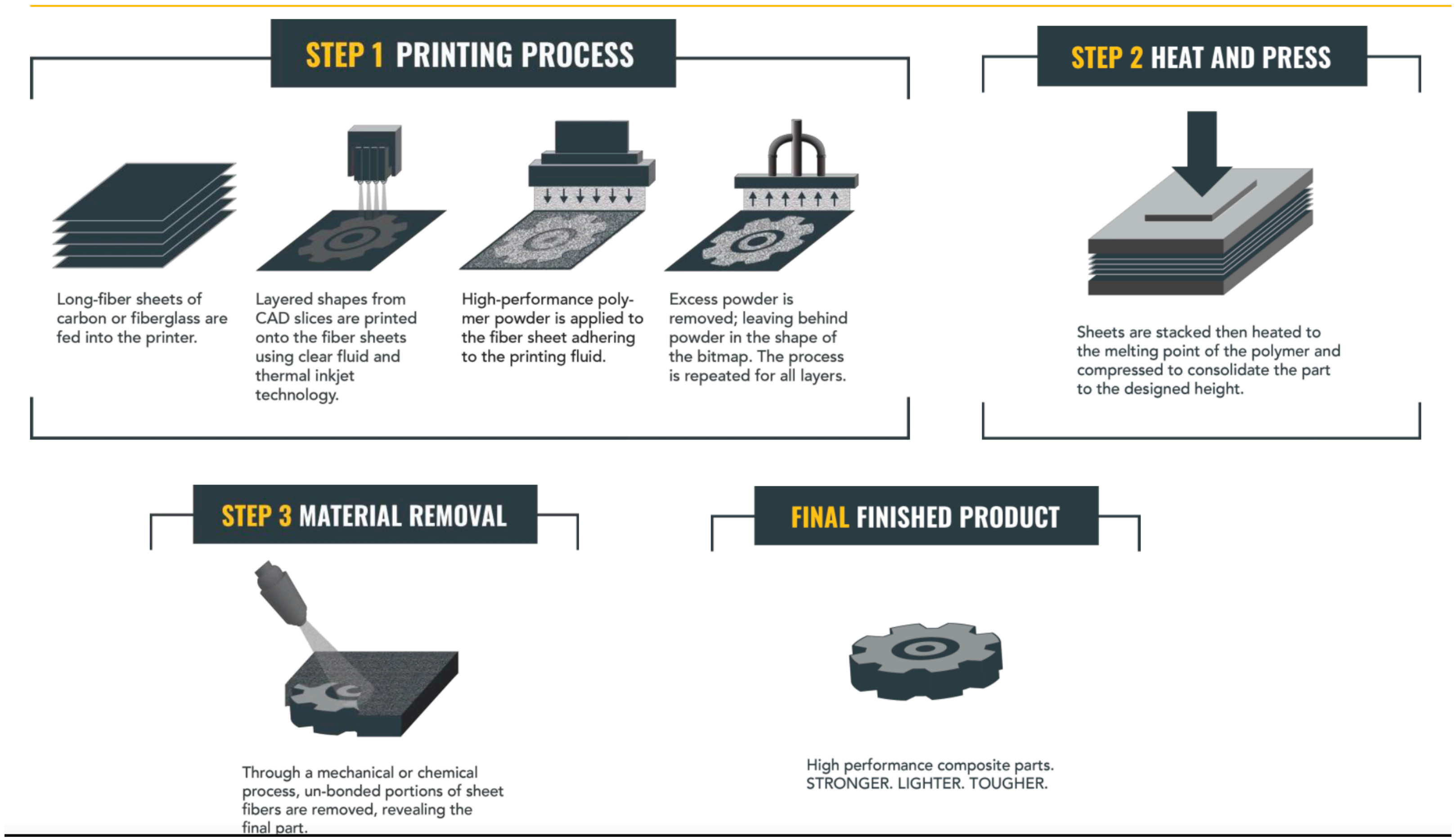
HP Multi Jet Fusion

- A number of filled and unfilled thermoplastics
- Open materials platform with certification program for vendors
- Materials Development Kit (MDK), a hardware system that allows companies to test 3D printing powders before bringing the materials to HP for certification.
- HP 3D High Reusability PA 12 Production Material 3D Inker thermoplastic powder
  - $6,522.58 for 286.6 lbs (~$23/lb)
  - Cosmetic grade PA 12 powder ~$3./lb
- Economics critically dependent on powder recovery and reusability

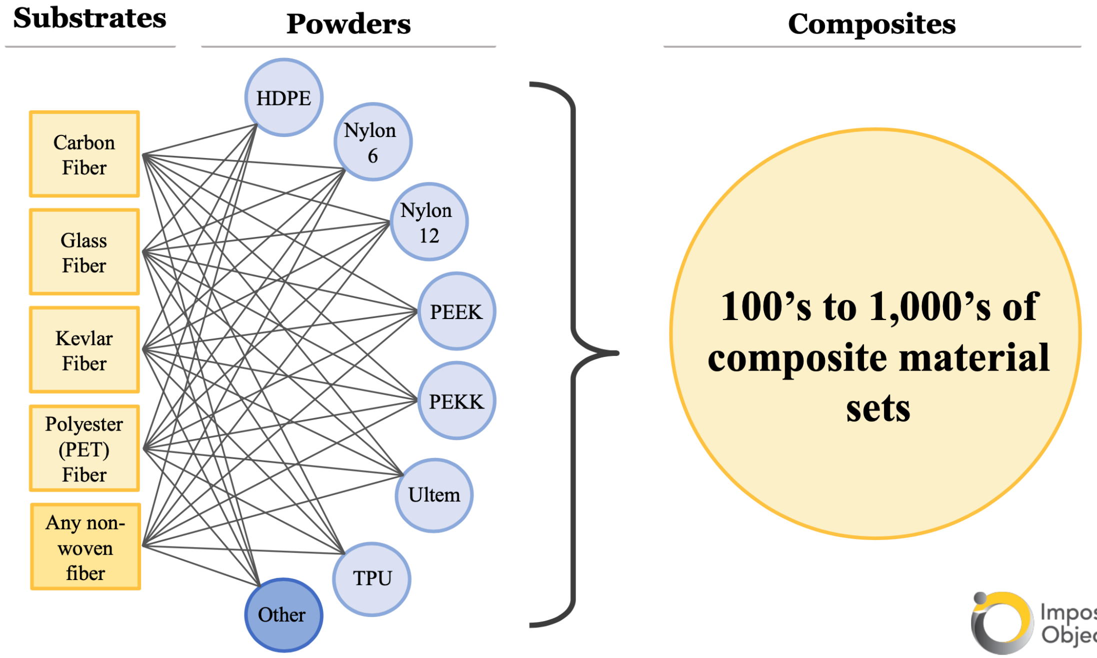
Composite Based Additive Manufacturing

- Based on veils of reinforcing fiber (carbon, glass, ceramic, elastomeric, …)
- IJ image on the veil
- Powder applied
- Non-adherent powder removed
- Completed layer set heated and compressed
- Non-imaged veil removed by sand blasting

Composite Based Additive Manufacturing (CBAM)



Composite Based Additive Manufacturing (CBAM)



Impossible Objects

What are the trends?

- Increasing number of firms (lots of venture funding, M&A on the way up)
- Increasing diversity of applications
- Increasing speed
  - 3D printers on the market in 2019 are ~2x as fast as those that were available in 2014
- Increasing build volume
  - A few years ago the big ones were 1l, now 27l is not uncommon – and on the high-end Oak Ridge National Laboratory with its Big Area Additive Manufacturing (BAAM) technology not to mention bridges and houses
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  - Number of materials that can be printed more than doubled in the last 5 years
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