Additive Manufacturing:
An Overview of the Technology and Its Promise

TURI Spring Continuing Education Conference

April 25, 2018

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Presentation Outline

- What is Additive Manufacturing?
- Why are people interested?
- Types of technologies
- Who are the players in Additive Manufacturing?
- Markets and applications
- Future trends

Types of Manufacturing

Cutting

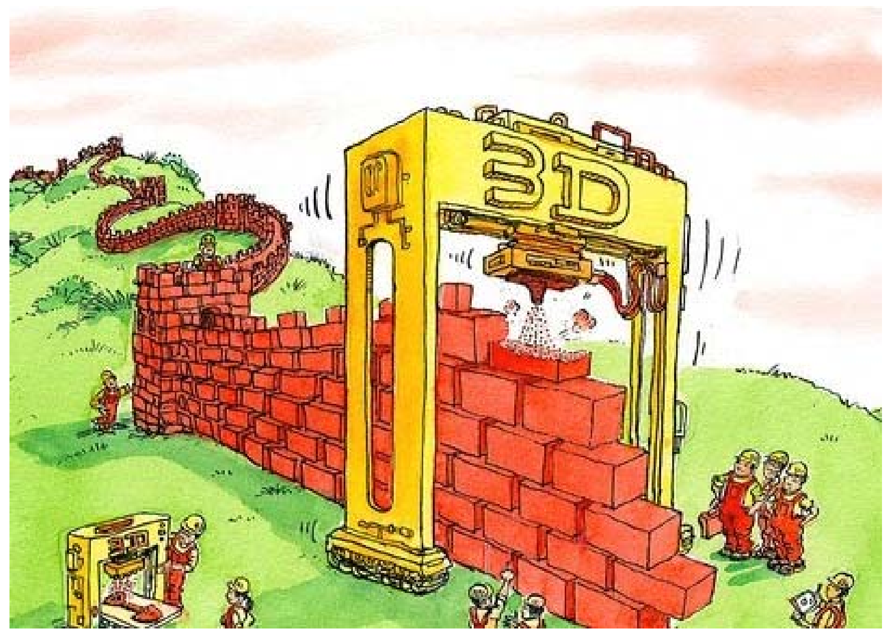
Subtractive Manufacturing

Forming

Additive Manufacturing

Subtractive vs. Additive

Subtractive vs. Additive



Additive Manufacturing: Definition

- A process of making a three-dimensional solid object by adding material
- ASTM F2792: Additive manufacturing is defined as the process of **joining materials** to make objects from **3D model data**, usually layer upon layer, as opposed to subtractive manufacturing methodologies.
- Additive Manufacturing is often abbreviated as **AM**

AM vs. 3D Printing

- 3D Printing is defined as the fabrication of objects through the deposition of a material using a print head, nozzle, or other printer technology

- The term is often used synonymously with AM

- 3D printing is often abbreviated as **3DP**

3D Printing: Video

Other Terms …

In addition to Additive Manufacturing (AM and 3D Printing (3DP), you may hear:

- Direct Digital Manufacturing (DDM)
- Rapid Prototyping (RP)

All of these terms and definitions touch on the advantages of this technology

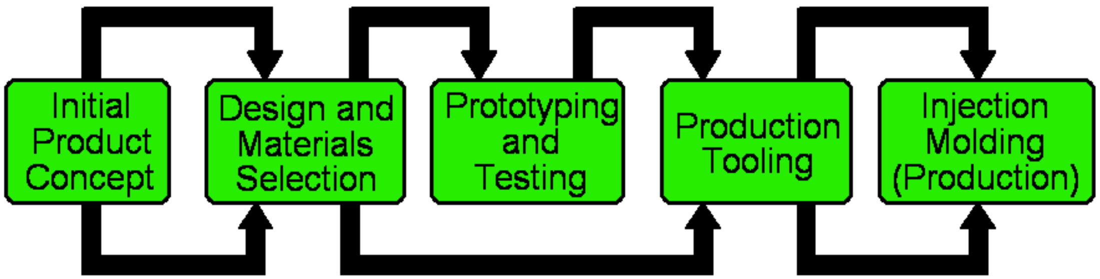
AM Advantages

- Design freedom
- Design iterations
- Time savings
- Cost savings

Design Freedom

Design Iterations

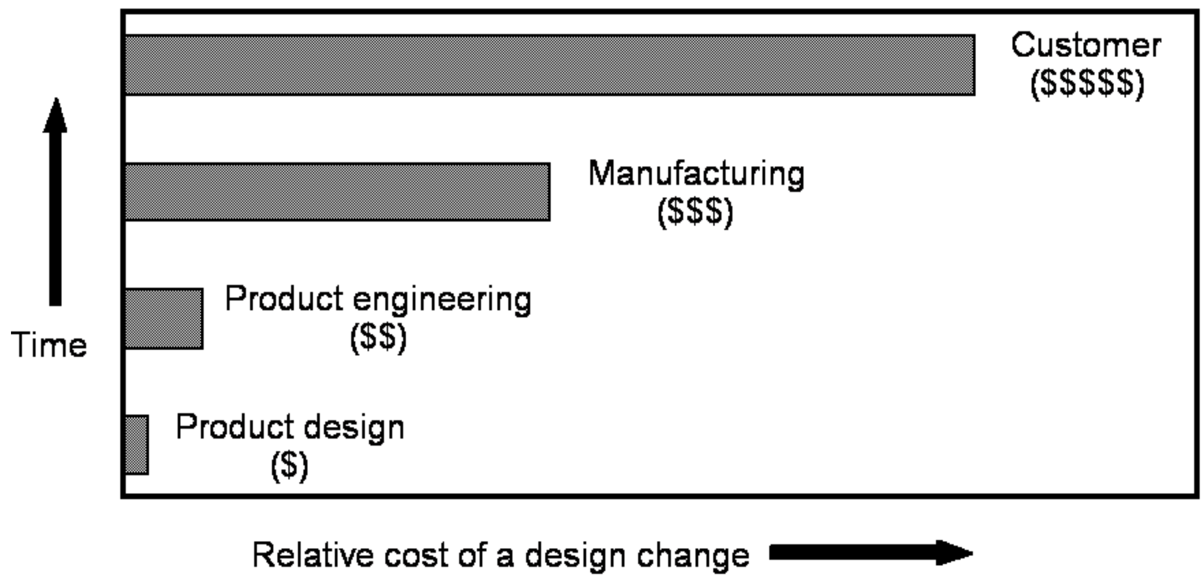
(a) Plastic Product Development Cycle With Prototyping



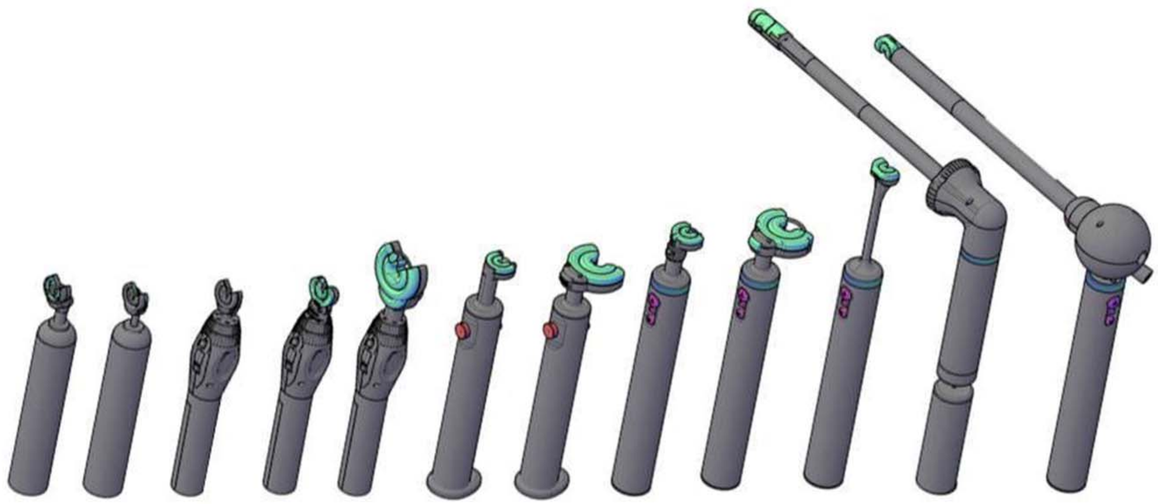
Prototyping helps catch and correct problems early

(b) Plastic Product Development Cycle Without Prototyping

Cost to correct a problem increases exponentially with time



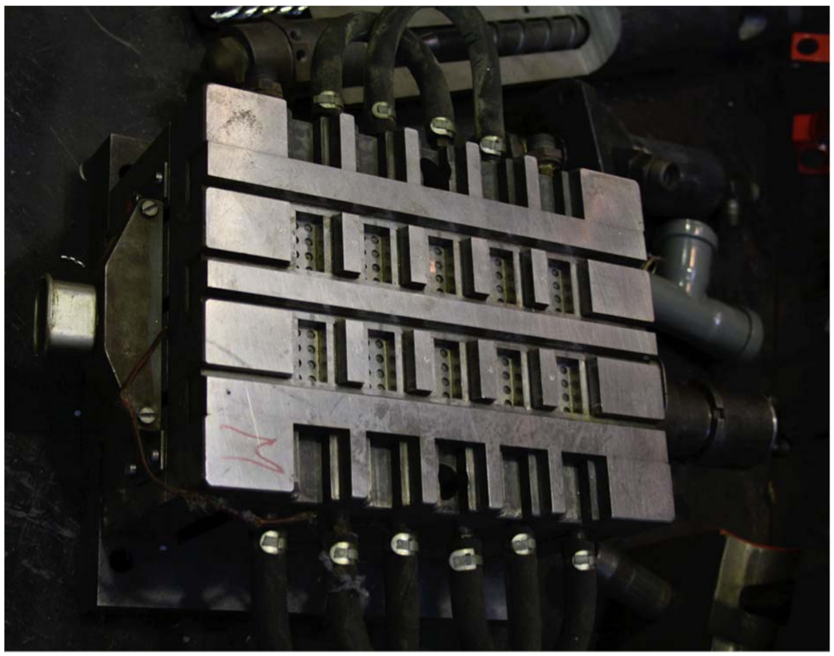
Design Iterations



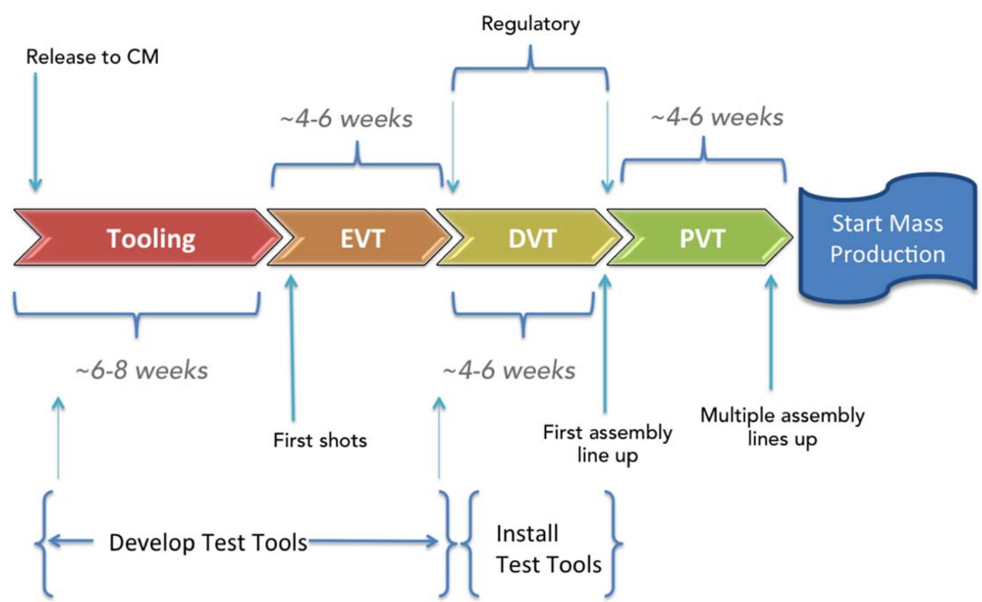
Enhance quality and design

https://formlabs.com/blog/ultimate-guide-to-rapid-prototyping/

Time Savings



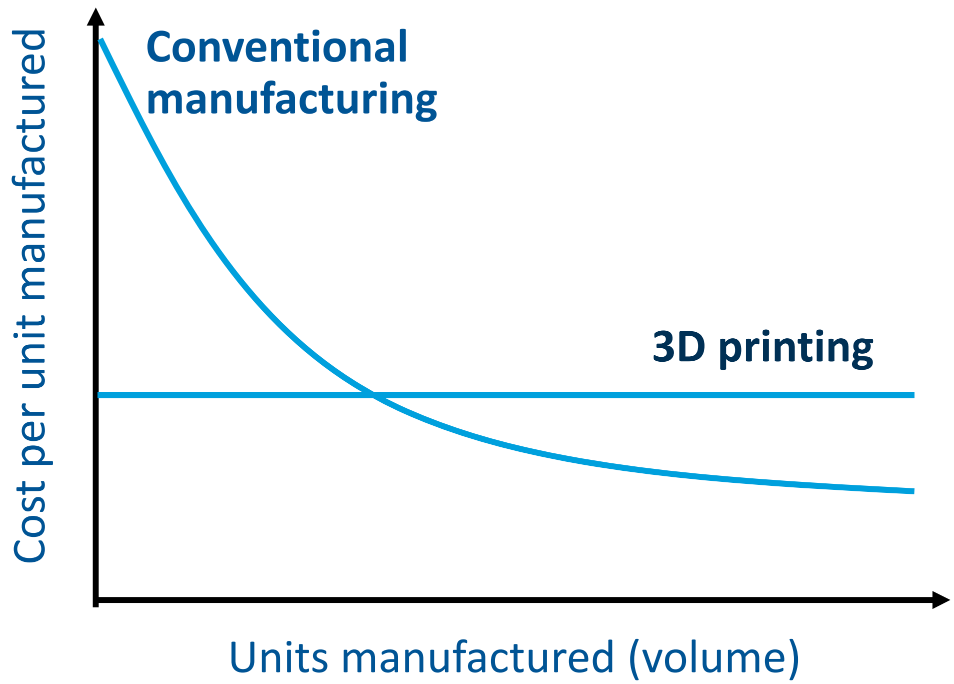
Mold for LEGO® Production

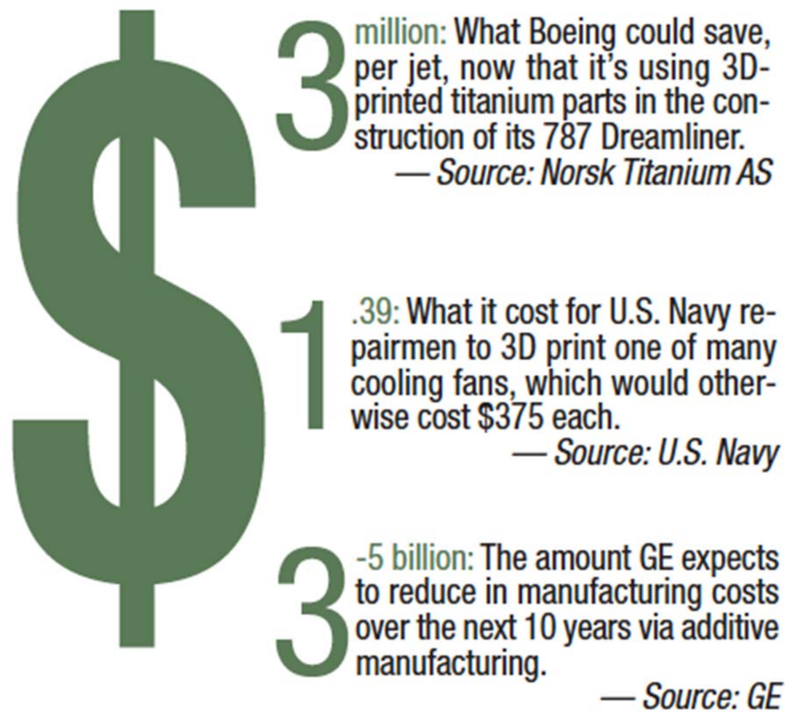


4 to 6 MONTHS!

http://mindtribe.com/2016/08/how-long-does-it-take-to-manufacture-a-hardware-product/

Cost Savings





Small production runs become cost effective

http://www.digitaleng.news/de/numbers-3d-printing/

Types of AM Technologies

American Society for Testing Materials (ASTM) (committee F42) defines seven process categories for Additive Manufacturing technologies:

Material Extrusion

FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication

Sheet Lamination

UC	Ultrasonic Consolidation
LOM	Fused Filament Fabrication

Binder Jetting

CJP	ColorJet Printing
PP	Plaster-based 3D Printing

Vat Photopolymerization

SLA	Stereolithography
DLP	Digital Light Processing
3SP	Scan, Spin, & Selectively Photocure
CLIP	Continuous Liquid Interface Production

Powder Bed Fusion

SLS	Selective Laser Sintering
DMLS	Direct Metal Laser Sintering
EBM	Electron Beam Melting
SHS	Selective Heat Sintering

Material Jetting

MJP	MultiJet Printing
PJ	PolyJet

Directed Energy Deposition

LMD	Laser Metal Deposition

Adapted from Stratasys Certification Learning Content

Types of AM Technologies

Today will focus on these as more heavily used technologies:

Material Extrusion

FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication

Binder Jetting

CJP	ColorJet Printing

Vat Photopolymerization

SLA	Stereolithography
DLP	Digital Light Processing

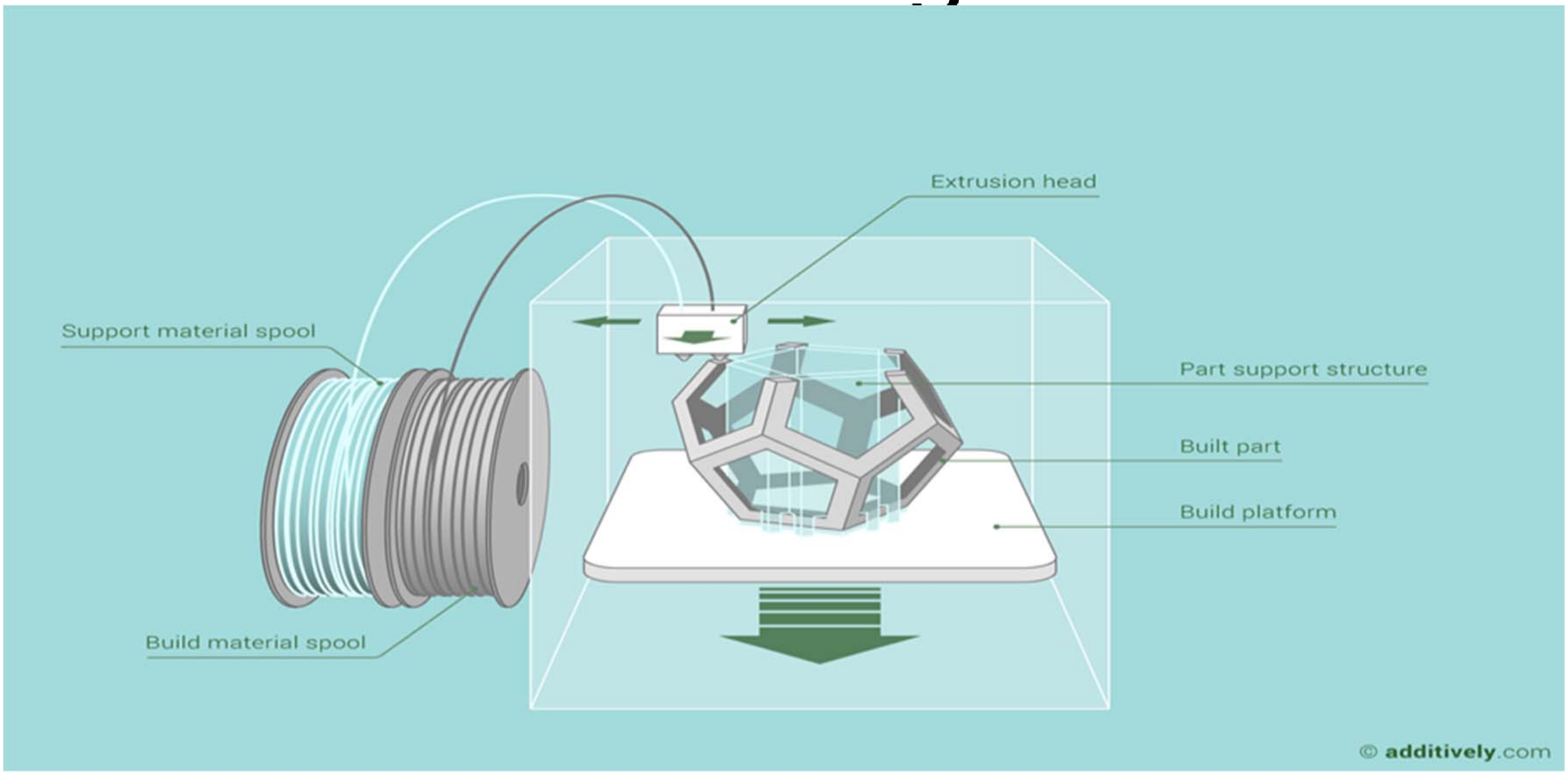
Powder Bed Fusion

SLS	Selective Laser Sintering
DMLS	Direct Metal Laser Sintering
EBM	Electron Beam Melting

Material Jetting

MJP	MultiJet Printing
PJ	PolyJet

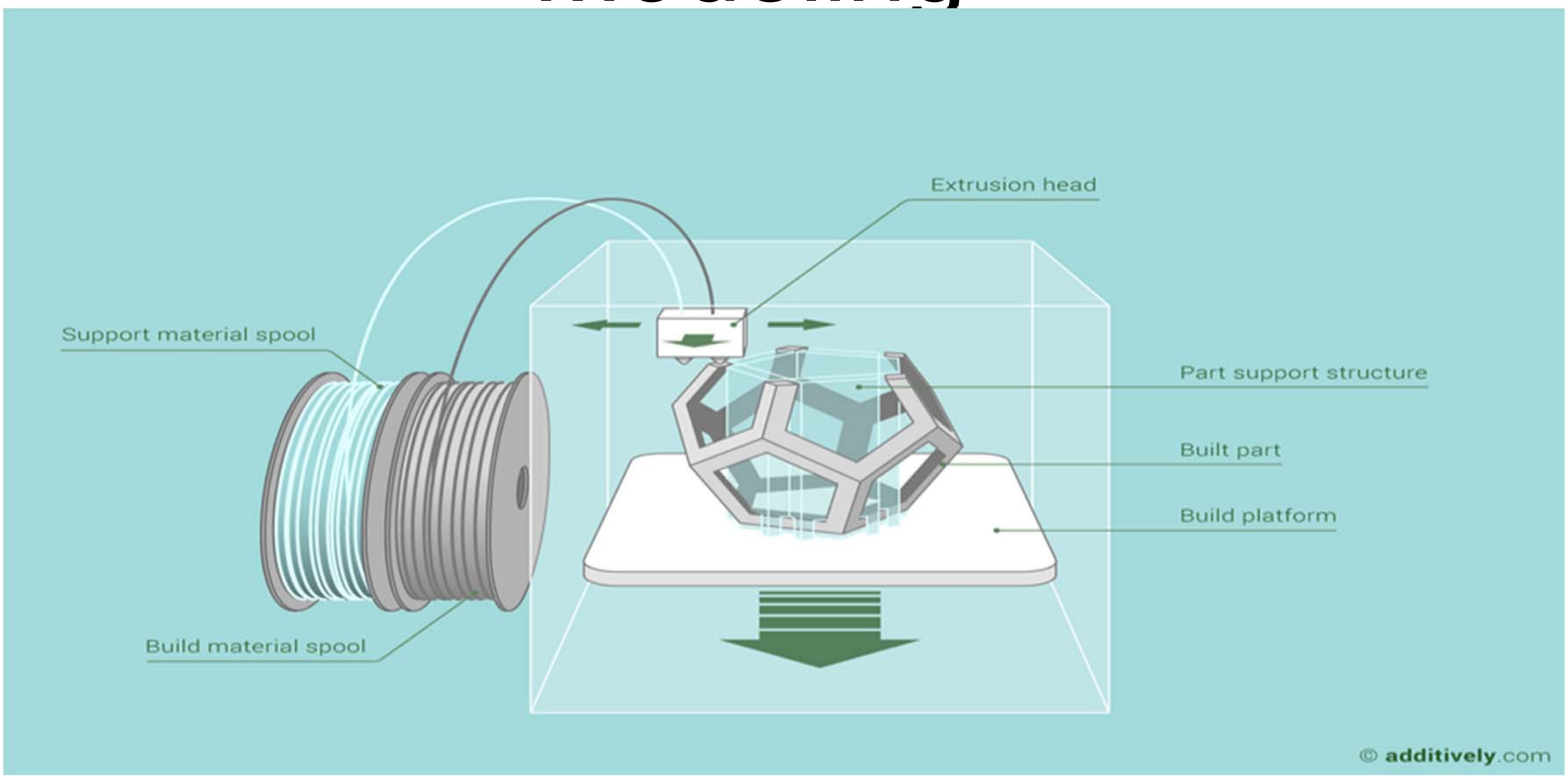
Fused Filament Fabrication/Fused Deposition Modeling



Process Overview

- Strands of material are melted and extruded onto a platform
- Strands weld to one another to form solid part
- Support material is broken or dissolved away

Fused Filament Fabrication/Fused Deposition Modeling



Strengths
- Fast prototypes – desktop printers
- Inexpensive relative to alternatives

Weaknesses
- Surface roughness due to layering
- 330-178 m (0.013 - 0.007") layer thickness
- Limited materials & properties

Commercial FDM Machines

stratasys

Materials

FDM Thermoplastics

- ABS*plus*
- ABSi
- ABS-M30
- ABS-M30i
- ABS-ESD7
- ASA
- FDM Nylon 6
- FDM Nylon 12
- FDM Nylon 12CF
- PC
- PC-ABS
- PC-ISO
- PLA
- PPSF/PPSU
- ST-130
- ULTEM 1010
- ULTEM 9085

Machines

Idea Series

- Mojo
- uPrint SE Plus

Design Series

Production Series

Precision

- Connex3
- Objet1000 Plus
- Stratasys J750

Performance

- Fortus 380/450mc
- Fortus 900mc

Consumer FDM Machines

MakerBot

•Build size up to 12” x 12” x 18”
•Materials: ABS and/or PLA
•List price: $2,000 to $6,500

Rep Rap

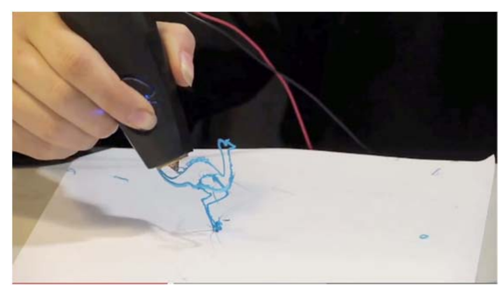
•Large variety of companies
•Maker Gear 8” x10” x 8” build
•List price: $1,800

Cube

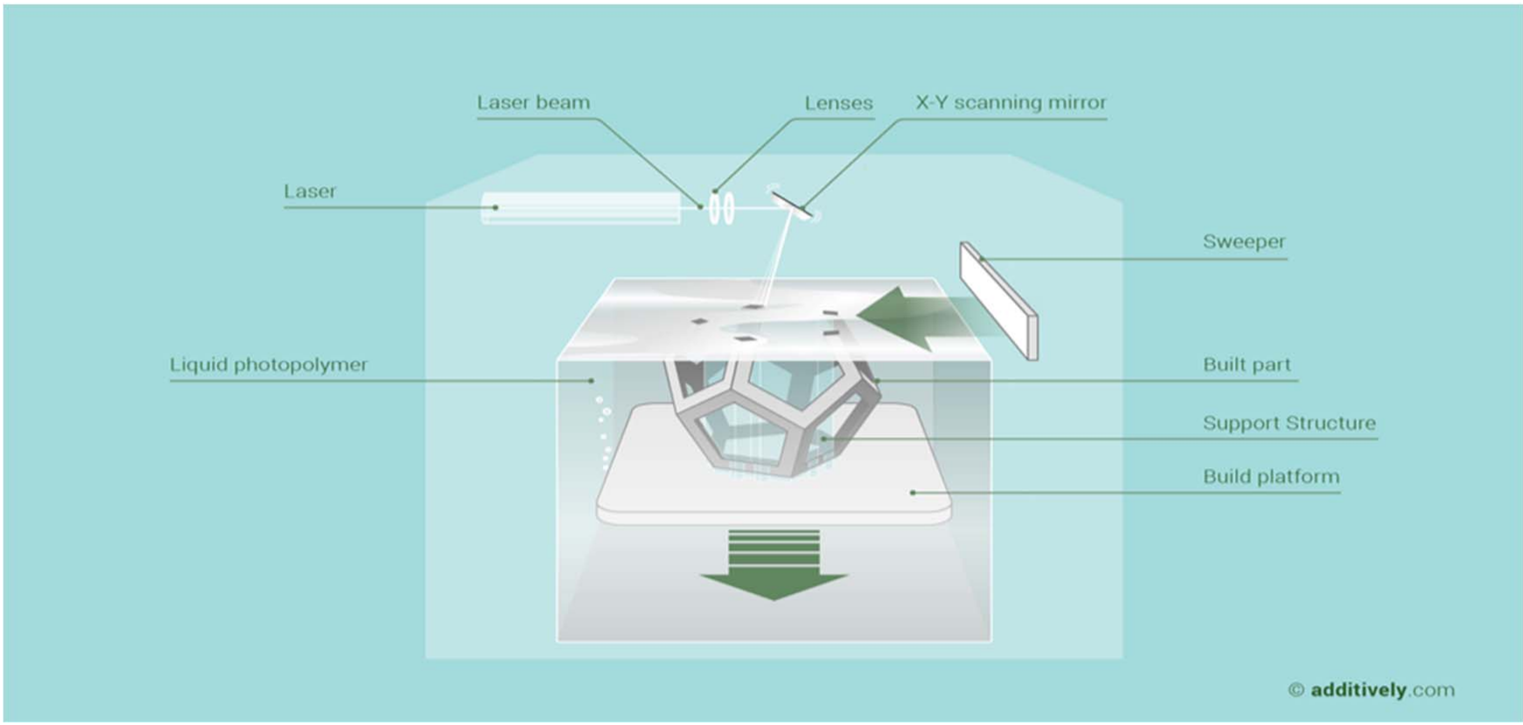
•Build size: 6” x 6” x 6”
•Materials: ABS or PLA
•List price: $1,300

3Doodler

•Build size: dictated by person
•Materials: ABS or PLA
•List price: $100



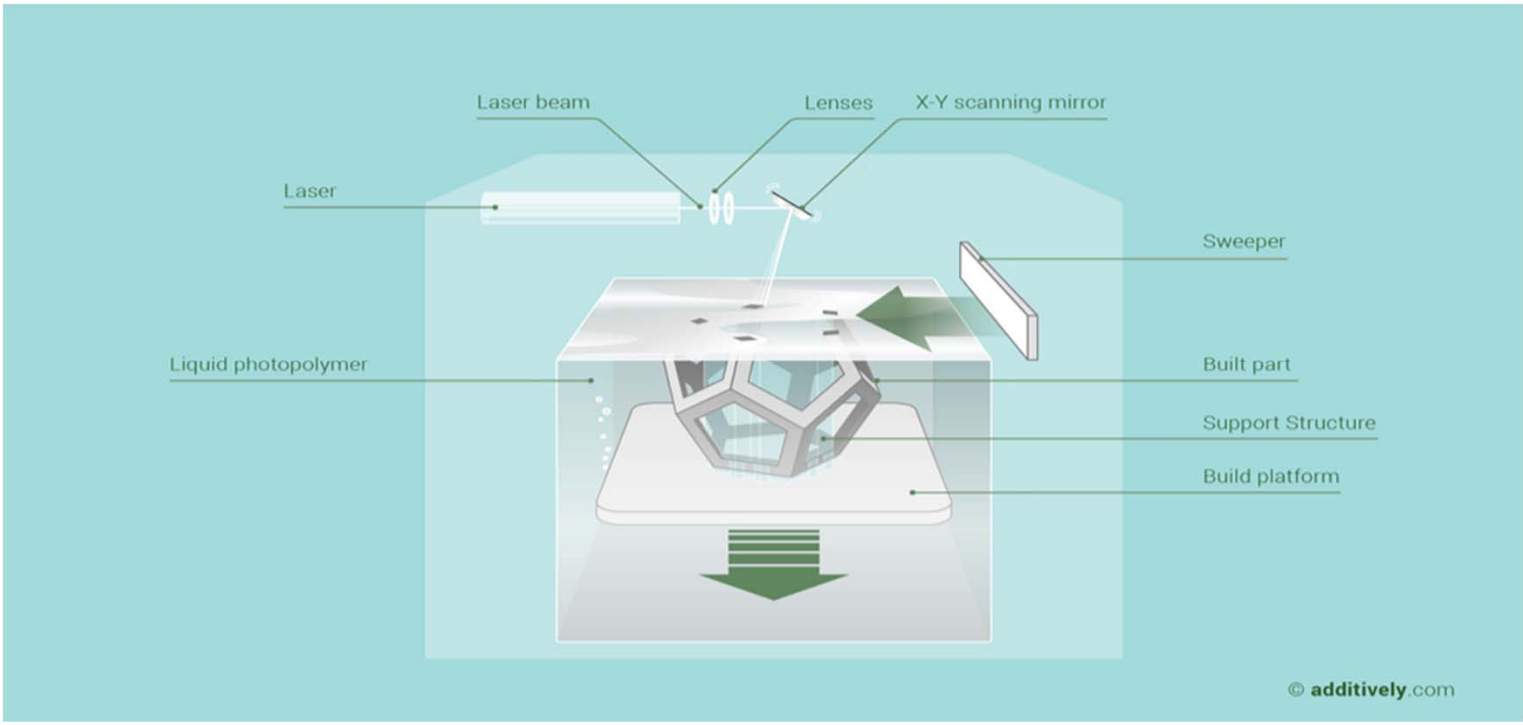
Vat Polymerization



Process Overview

- UV laser cures photopolymer to create part (thin supports also built)
- Parts cured in UV oven
- Support material cut away

Vat Polymerization



Strengths

- Highly accurate models (150 to 50 micron, 0.006“ to 0.002” layers)

Weaknesses

- Not as fast as FDM
- More costly equipment
- Hard to keep clean

Commercial SLA

3D Systems ®

3D SYSTEMS

Carbon ®

Carbon

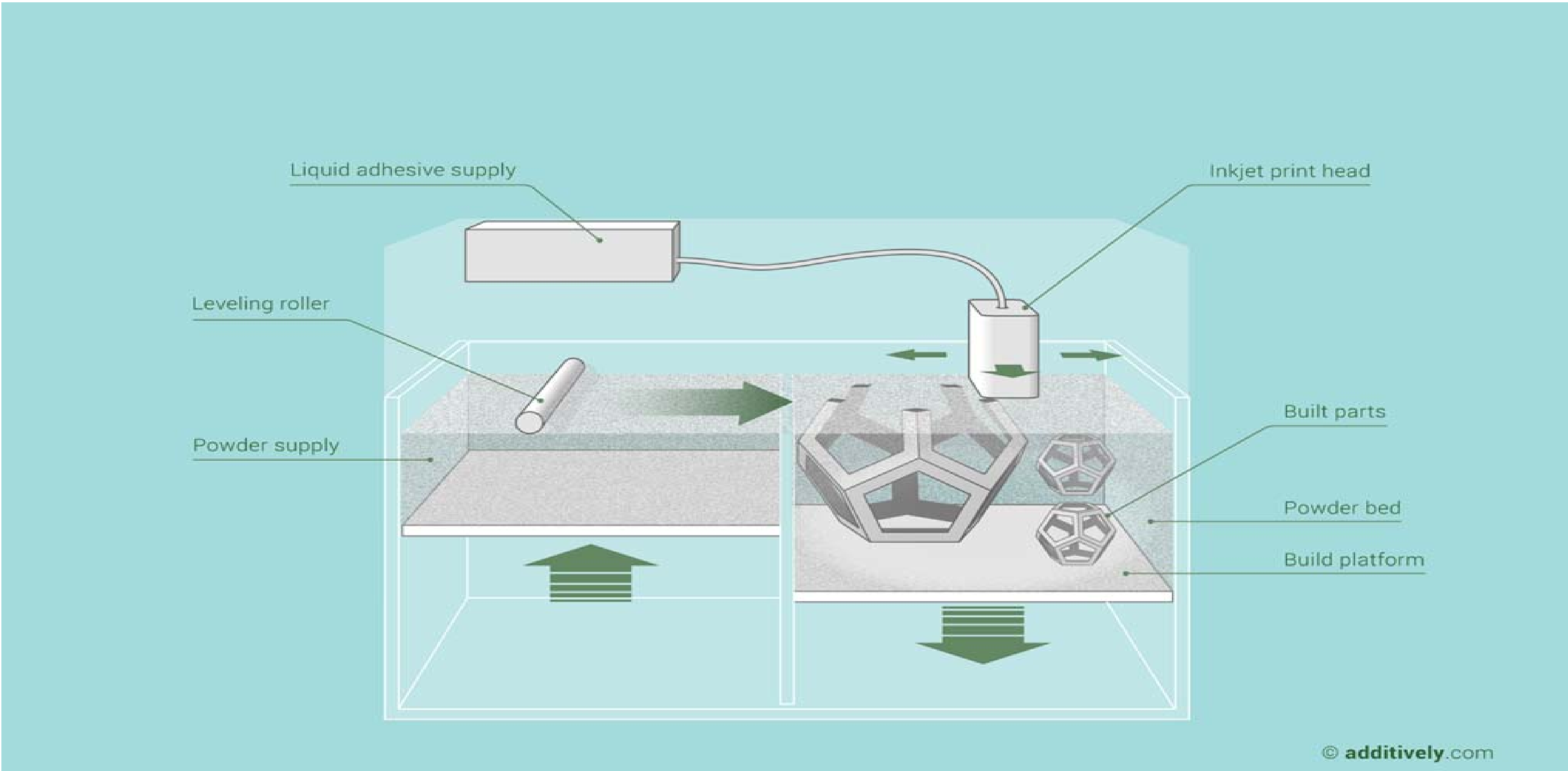
EnvisionTec ®

envisionTEC

Material Options

- ABS, PP, PC like
- High temperature
- Bio-compatible
- Transparent → Opaque
- Ceramic reinforced composite

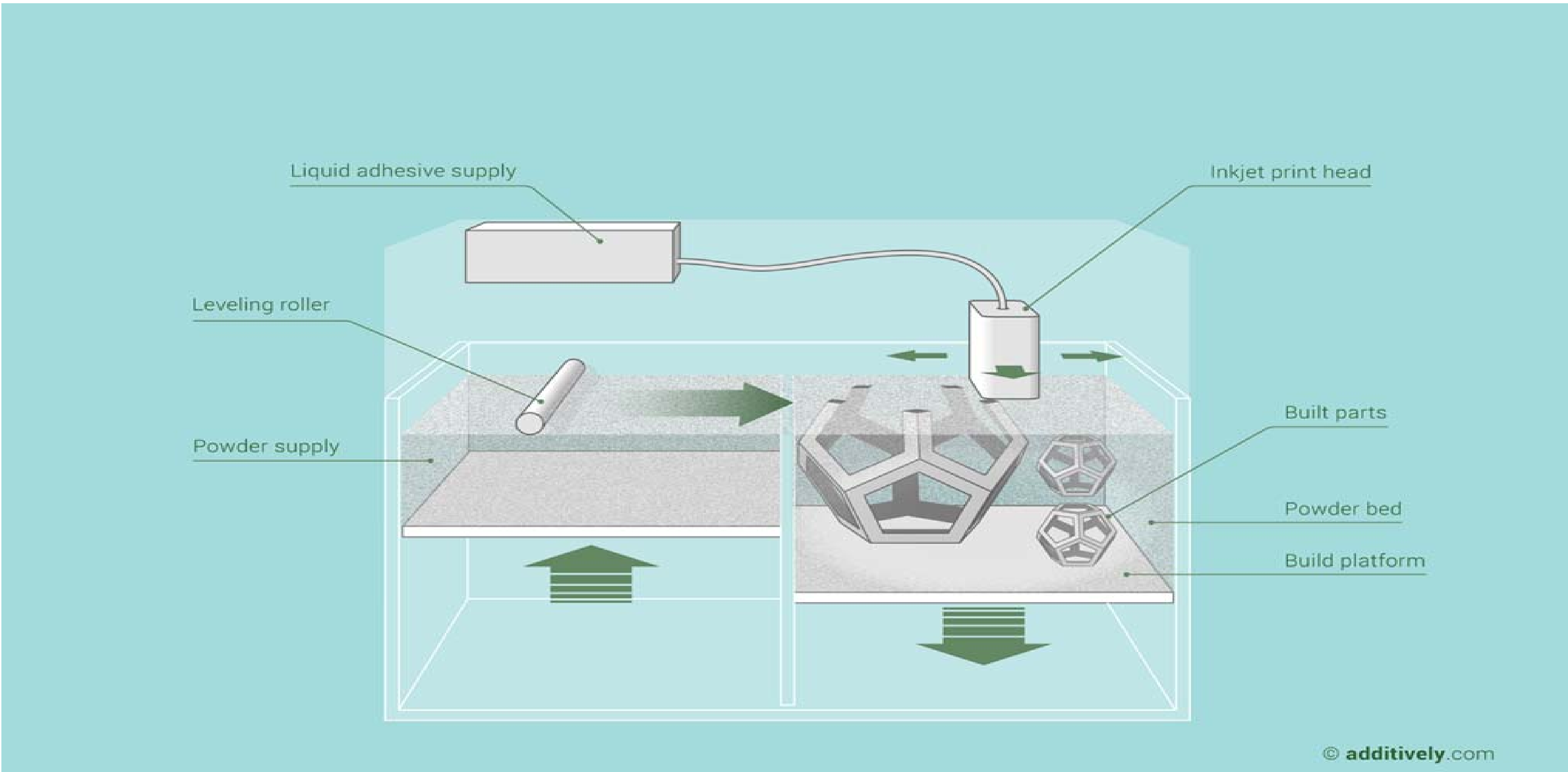
Binder Jetting



Process Overview

- A liquid binder agent is deposited by inkjet printhead onto a powder bed
- The powder bed is lowered and a new layer of powder is applied
- The part can be post-processed to increase its strength

Binder Jetting



Strengths
- Wide variety of powder materials
- Multi-color is possible
- Relatively fast and inexpensive

Weaknesses
- Limited mechanical properties
- Difficult to switch between materials between production runs

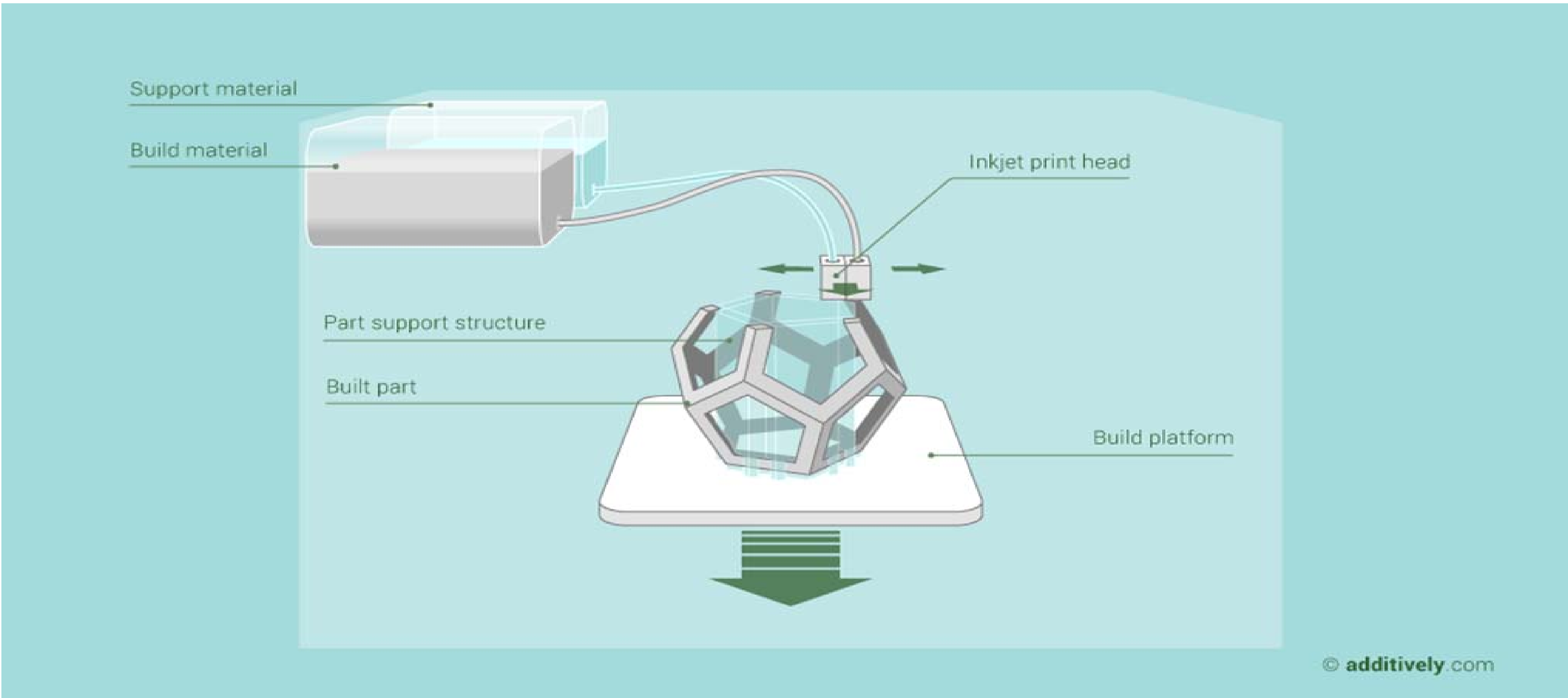
Commercial Binder Jetting

PRODUCTION PRINTERS
- Exerial
- S-Max+
- S-Max
- S-Print
- M-Print
- M-Flex

PROTOTYPING PRINTERS
- S-Print
- M-Flex

RESEARCH & EDUCATION PRINTERS
- M-Flex
- Innovent+®
- Innovent®

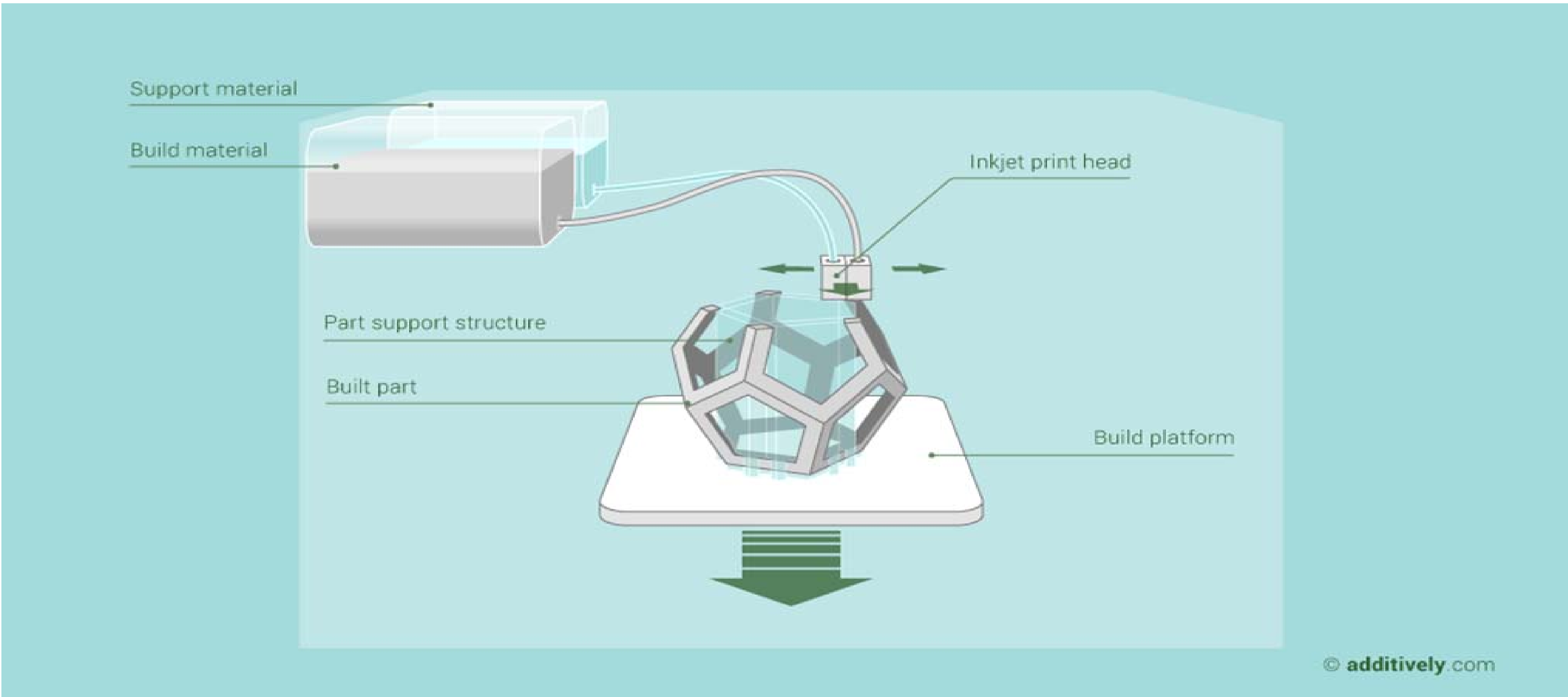
Material Jetting



Process Overview

- Melted wax is ejected from inkjet print heads
- The material solidifies upon cooling
- Supports are needed for overhangs

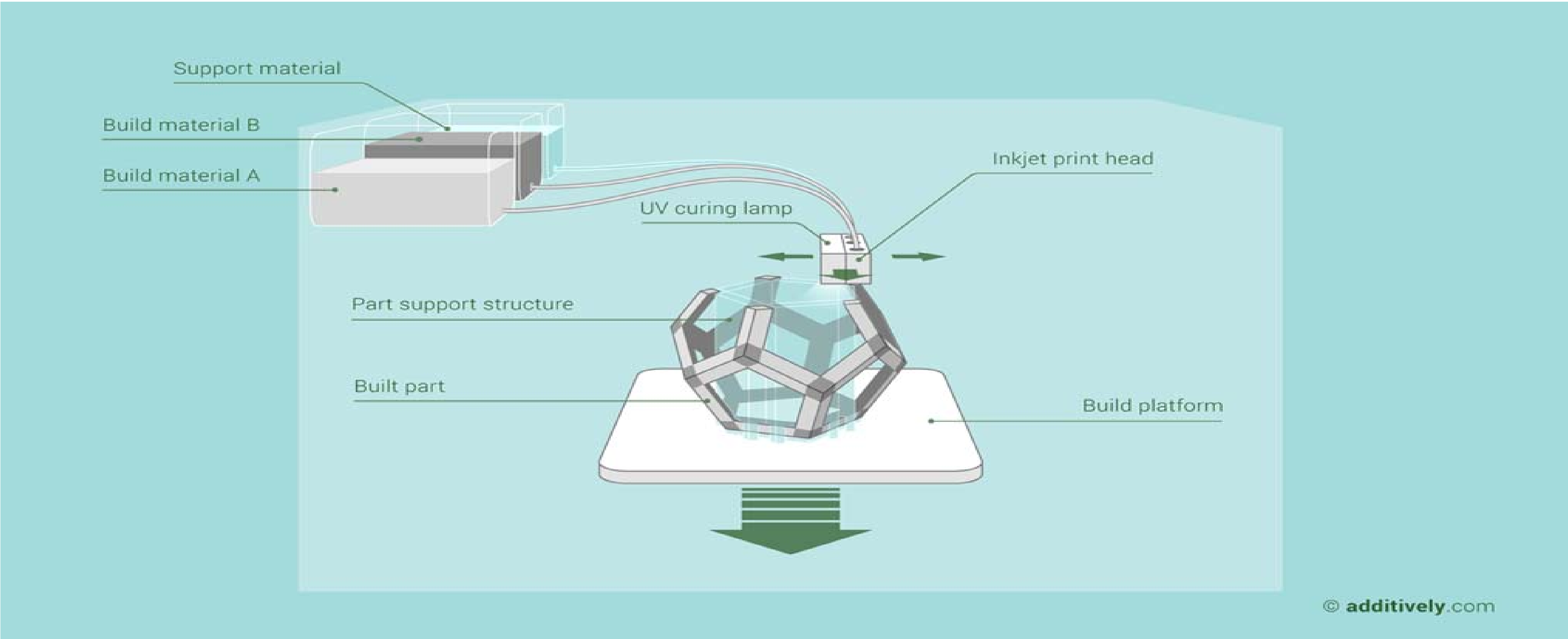
Material Jetting



Strengths
- Good accuracy
- Good surface finish

Weaknesses
- Limited material choices
- Limited mechanical properties

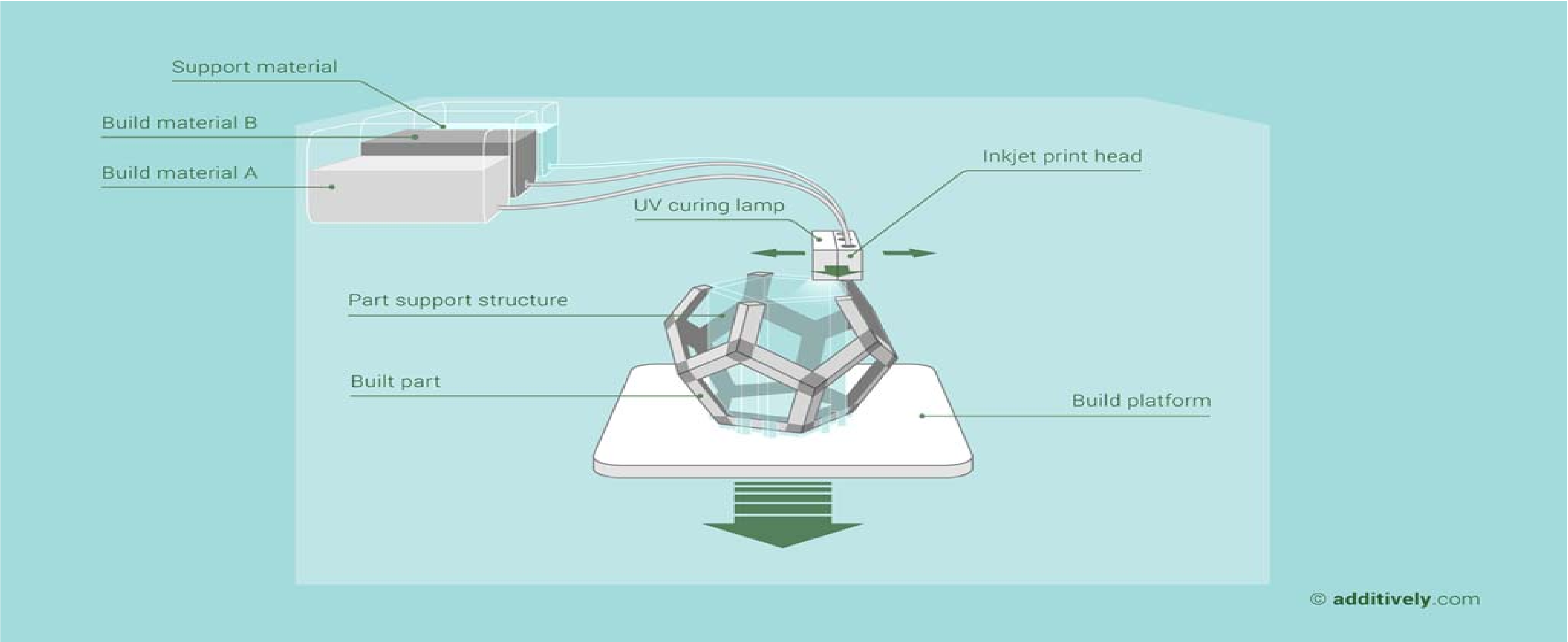
Photopolymer Jetting



Process Overview

- Liquid photocurable resin is ejected from inkjet print heads
- The material solidifies upon UV exposure
- Supports are needed for overhangs

Photopolymer Jetting

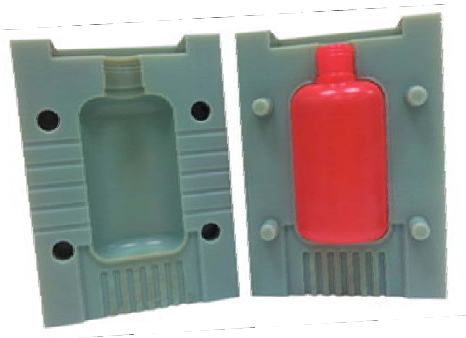


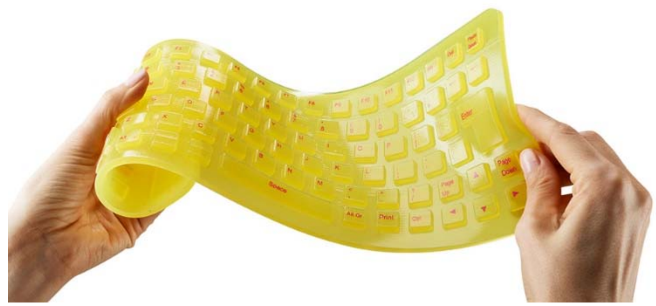
Strengths
- Multiple materials, 'digital' materials
- Great surface finish
- Good accuracy

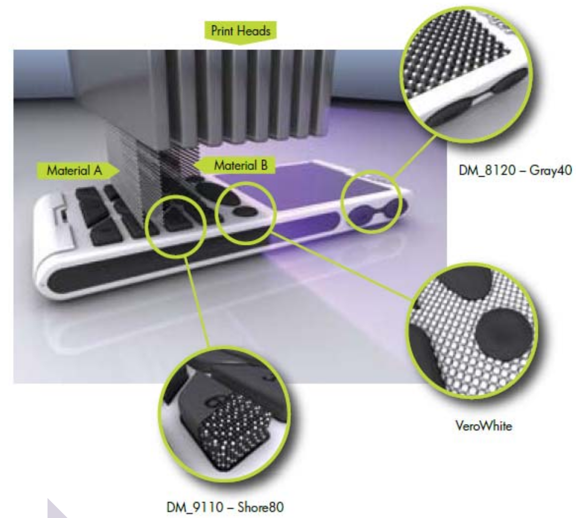
Weaknesses
- Low material stability over time
- Expensive
- Relatively slow production

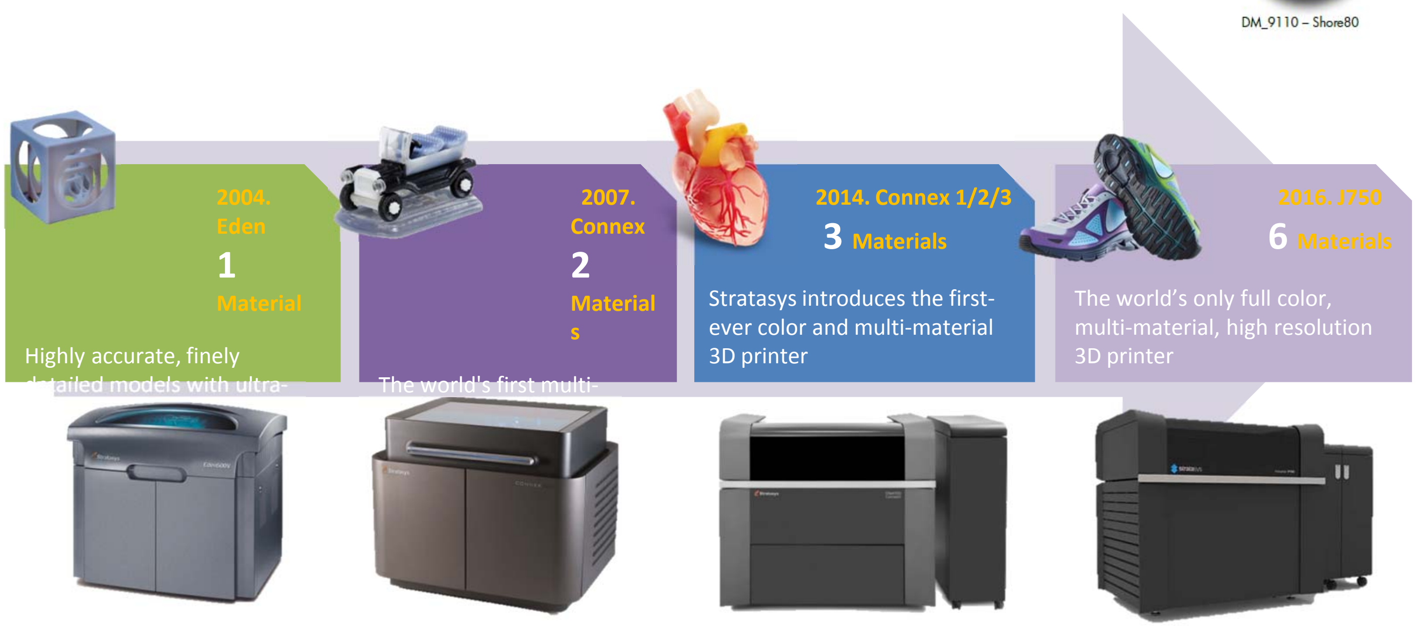
Commercial Photopolymer

Polyjet under Stratasys' Objet® brand name

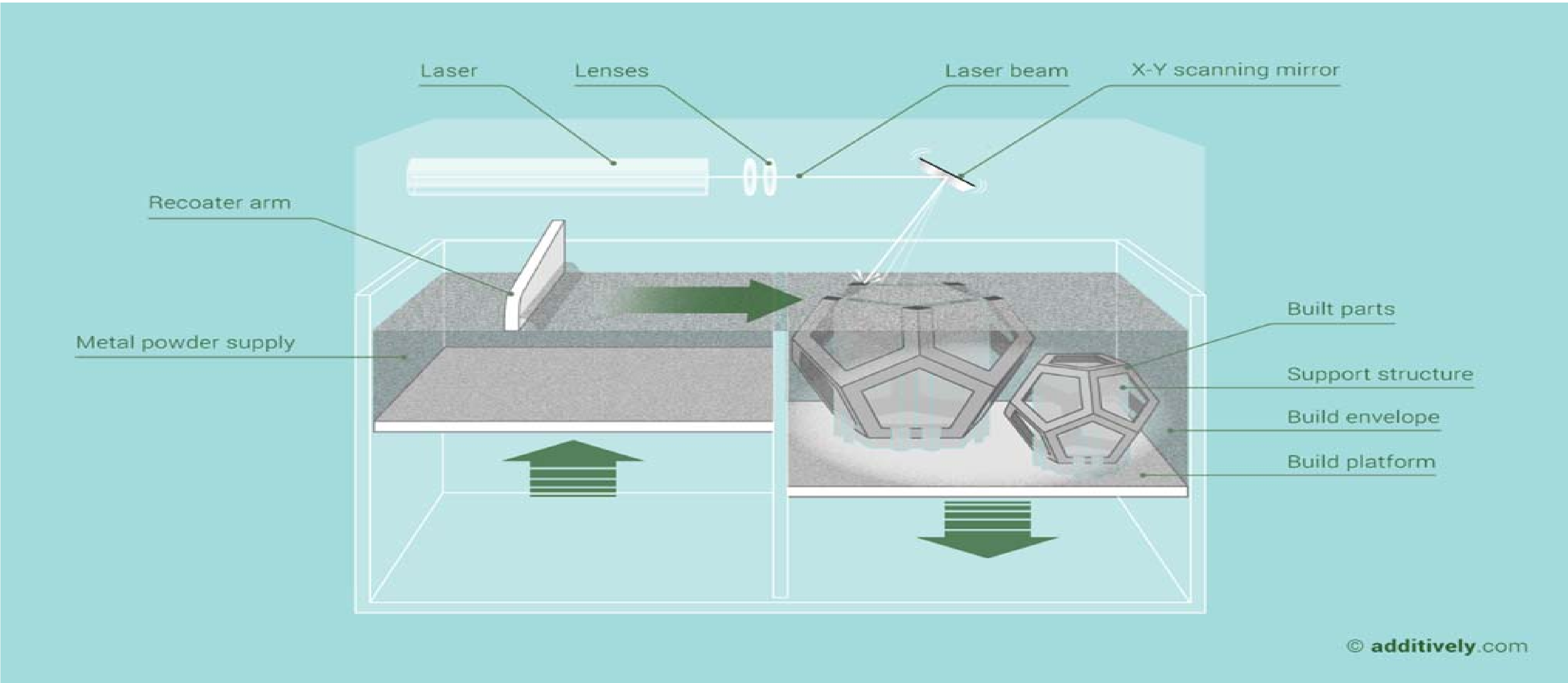








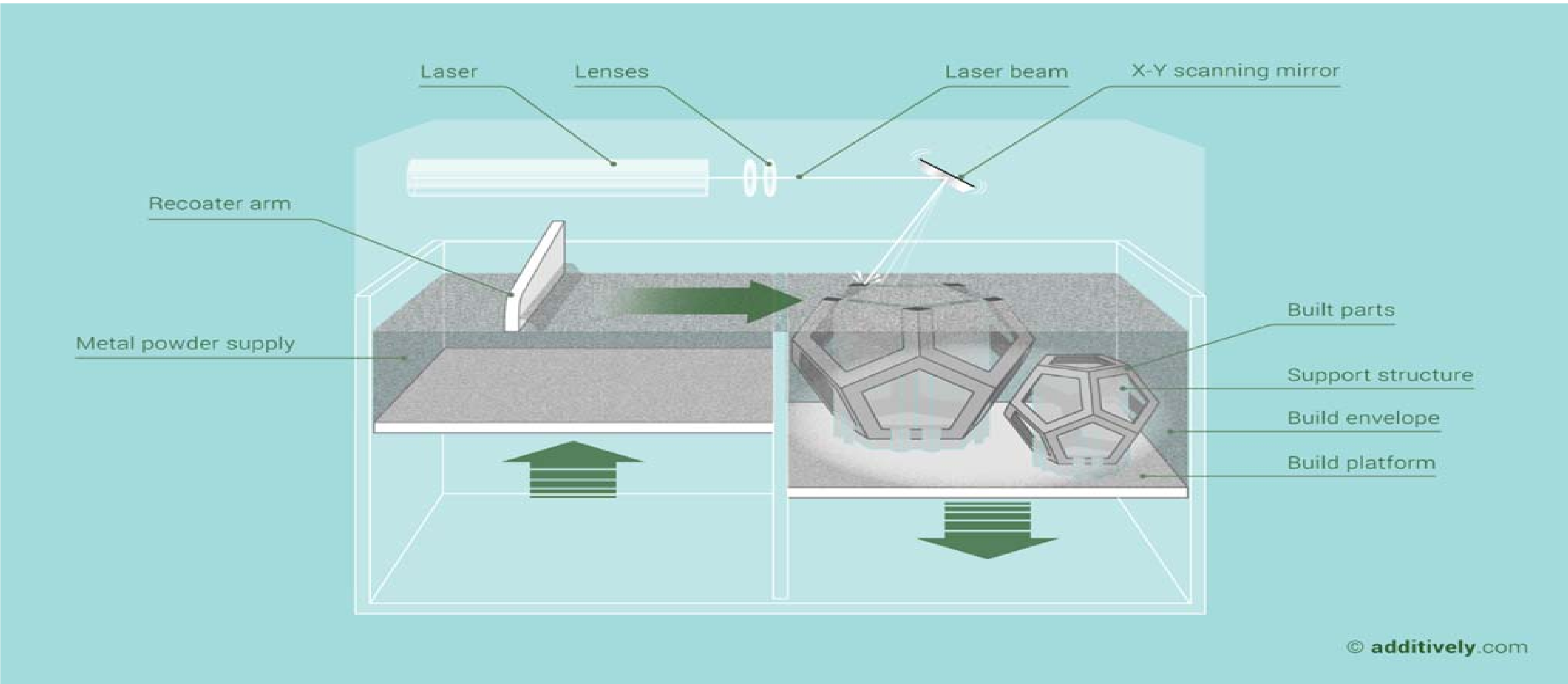
Powder Bed Fusion



Process Overview

- Laser beam (or e-beam) used to reach powder sintering/melting point
- The bed is lowered and a new layer of powder is added
- No support is needed

Powder Bed Fusion



Strengths
- Can manufacture metals directly
- Can manufacture semi-sintered ceramics

Weaknesses
- Relatively expensive
- Tolerances limited

Post-Processing Steps

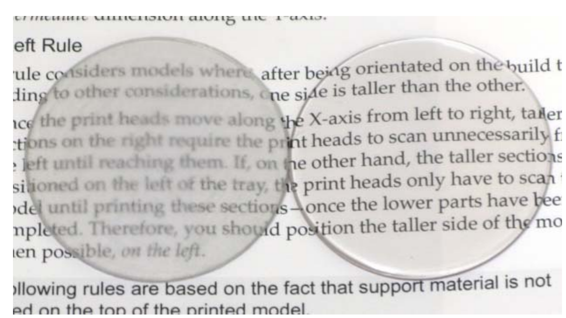
Processes that can be applied to a 3D printed parts after print to provide:

Look and Feel / Finishing	Mechanical Properties	Seal Adaptation
Mass Finishing	Composite method	Coating
Painting	Thermal treatment	Bio Computability
Transparency	Gluing	
Material mimic		
Smoothing		
Support removal		

This is NOT a "must do" step in the 3D printing process

BEFORE **AFTER**

BEFORE **AFTER**



Adapted from Stratasys Certification Learning Content

Markets & Applications

Aerospace

Automotive

Consumer Products

Medical

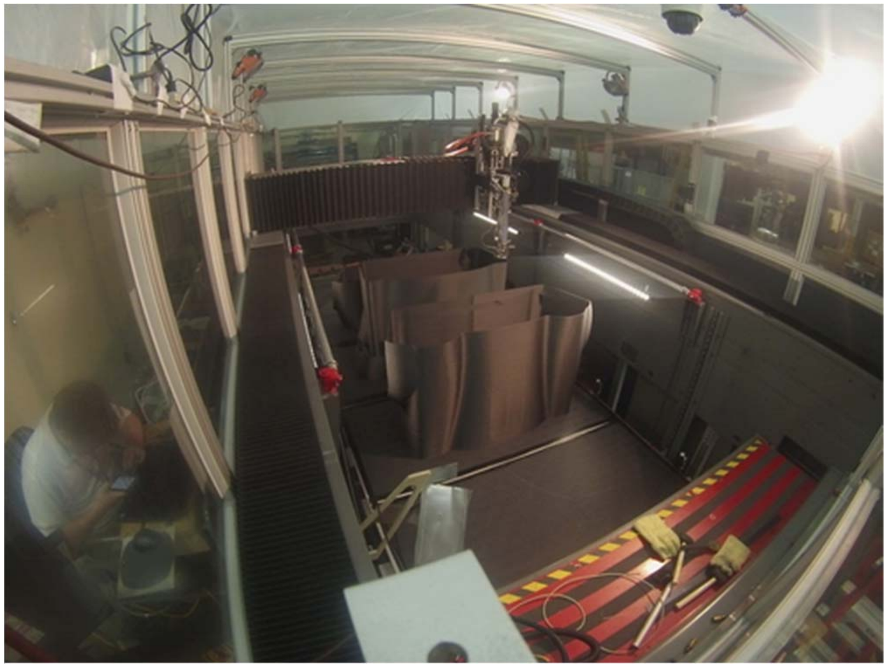
Dental

Manufacturing

In 2017: $6.06 Billion Industry, 17.4% Annual Growth

Automotive: BAAM

- BAAM: Big Area Additive Manufacturing

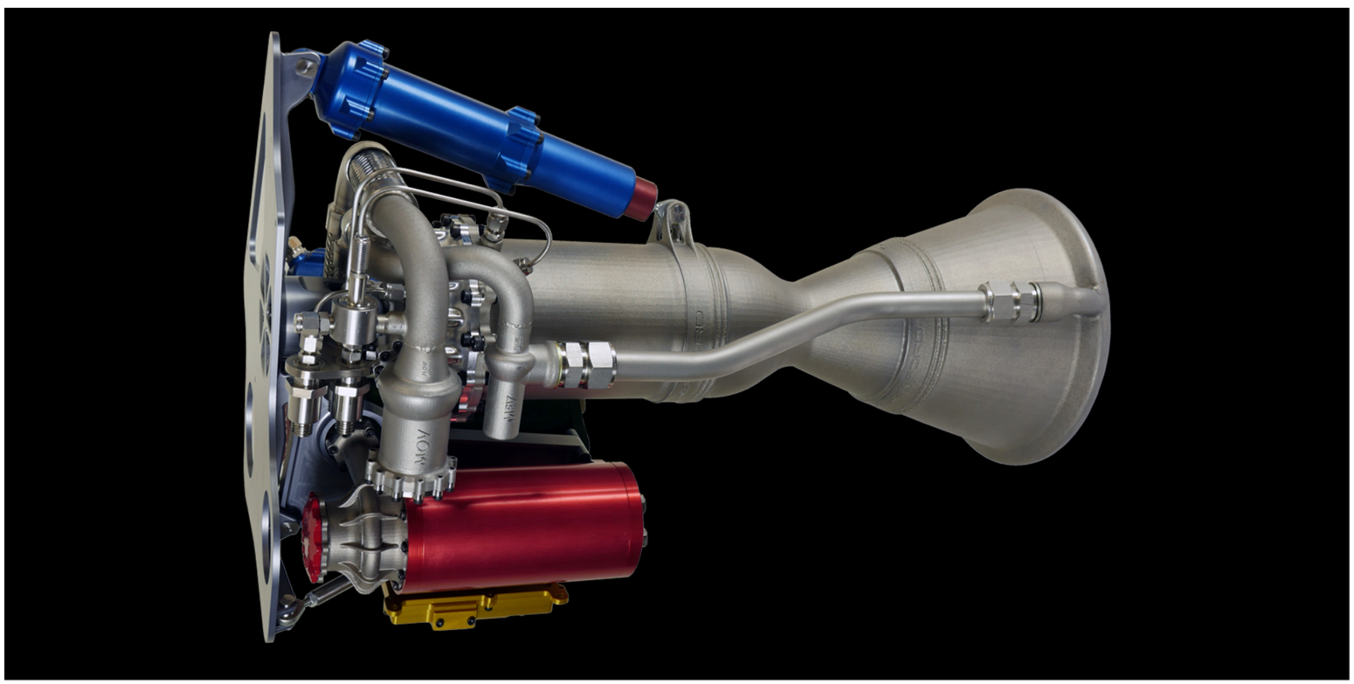


Printed the car structure in 44 hours

https://vimeo.com/146030156

Aerospace: Rocket Lab

“3D printed primary components. Rutherford is the first oxygen/hydrocarbon engine to **use 3D printing for all primary components** including its engine chamber, injector, pumps and main propellant valves. Using this process, Rocket Lab’s engineers have **created complex, yet lightweight, structures previously unattainable** through traditional techniques, **reducing the build time from months to days** and increasing affordability”



https://youtu.b
/2indPcalm-A

Dental: Invisalign Example

Scan teeth for 'Digital Impression'

Series of part files created

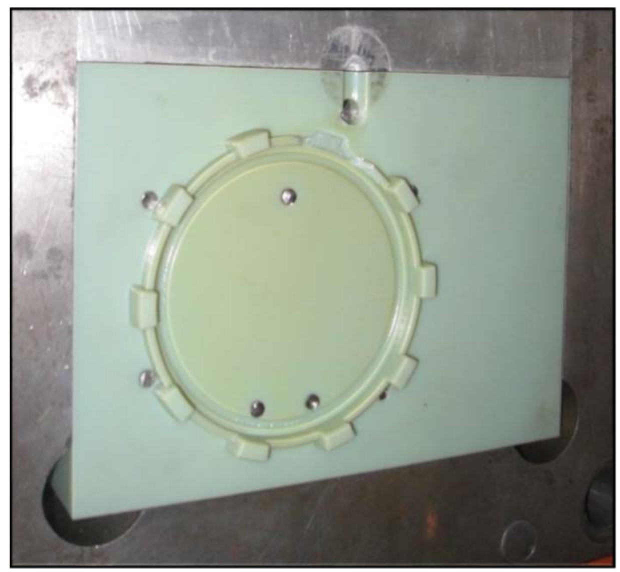
Printed at central factory

https://youtu.be/sDsIfaA5n1s

Manufacturing

Rapid Tooling for Injection Molding

- Utilize additive manufacturing for mold inserts
  - Objet, EOS, 3D Systems, others
- Advantages
  - Eliminates need to machine inserts
  - Faster turn-around time & reduced cost
- Disadvantages
  - Objet jetted photopolymer process
    - Long cycle time – 6+ minute to cool
    - Limited production volume: less than 100 parts
  - EOS direct metal process
    - Metal remains porous with high surface roughness
    - Ejection issues
  - Dimensional issues



Who's Who in AM?

- In 2017, 97 companies selling AM equipment and products

RANK	COMPANY	MATERIAL	REVENUE	GLOBAL REVENUE SHARE
1	Stratasys	Polymer	$100.5M	24%
2	EOS	Polymer & Metal	$73.2M	17%
3	HP	Polymer	$38.9M	9%
4	GE Additive	Metal	$37.7M	9%
5	3D Systems	Polymer & Metal	$29.4M	7%

In **polymers**, top 5: Stratasys, 3D Systems, EnvisionTEC, HP, Carbon
In **metals**, top 5: GE Additive, EOS, SLM, TRUMPF, 3D Systems

https://www.engineering.com/AdvancedManufacturing/ArticleID/16296/Industrial-3D-Printing-Made-Impressive-Gains-in-2017And-Things-Are-Looking-Up.aspx

UMASS LOWELL

America Makes

SHAP3D

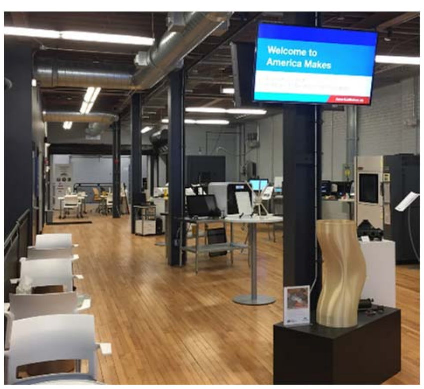
134	50	30
Silver Members	Gold Members	Platinum Members

Industrial, Government, and Academic Partners

Our **Projects**

- 1082 Measurement Science for Advanced Manufacturing (MSAM)
- 4006 Maturation of High-Temperature SLS Technologies & Infrastructure
- 4055 A Low-cost Industrial Multi3D System for 3D Electronics Manufacturing
- 4040 Development & Demonstration of an Open layered Protocol for Powder Bed AM
- 4064 Multimaterial 3D Printing of Electronics & Structures

Research projects funded



Innovation Factory
& Satellite Location

Industry Events

- Science in the Age of Experience
  - Boston June 18-21 2018!
- RAPID (happening now)
- AMUG – Additive Manufacturing Users Group

Full list: https://3dprintingforbeginners.com/fairs_events/

National Science Foundation I/UCRC:

Industry/University Cooperative Research Centers Program

SHAP3D

Science of Heterogeneous Additive Printing of 3D Materials

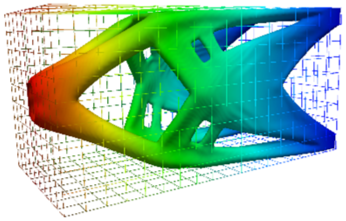
- Cutting-edge pre-competitive fundamental research in science, engineering, technology area(s) of interest to industry
- Members (Industry, Nonprofits) guide the direction of Center research through active involvement and mentoring

UMASS University of Massachusetts Lowell

UCONN

GEORGIA TECH

Thrust Areas

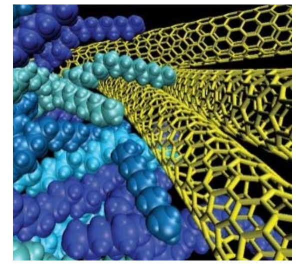


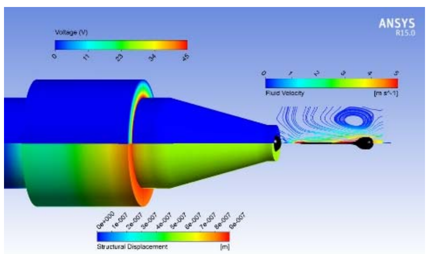
Design

Achieve unique properties through design

Develop novel and enhanced materials

Material





Modeling

Formulate and validate models

Improve and create new concepts

Printing Methods

Applica-tions

Emerging applications (e.g., biomedical)

Planning Meeting Industry Attendees

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SHAP3D

AUTODESK

Anton Paar

BAE SYSTEMS

CCAT Connecticut Center for Advanced Technology, Inc.

Baystate Health

BOEING

CABOT

3DFortify

DRAPER

GE

hp

HUTCHINSON®

Integrity Industrial Ink Jet Integration

MASSACHUSETTS TECHNOLOGY COLLABORATIVE

Medtronic

MIDÉ

MTS®

Myriant

nanocomp TECHNOLOGIES, INC.

new balance

US ARMY NATICK SOLDIER RD&E CENTER

PHOENIX MANUFACTURING

R&D technologies

Raytheon

ROGERS CORPORATION

سابك sabic

SAINT-GOBAIN

Sandia National Laboratories

SMC®

stratasys

tsi

VENTUREWELL™

vibram®

UMass Lowell Site

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Composites/mechanics

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Printed meta/electronics

Carol Barry
Micro/nano processing

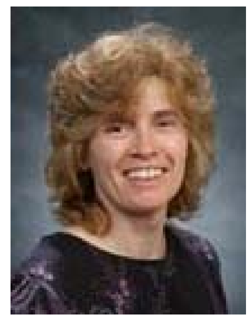
Bridgette Budhlall
Adaptive colloids/emulsions

Gulden Camci-Unal
Biomaterials & fabrication

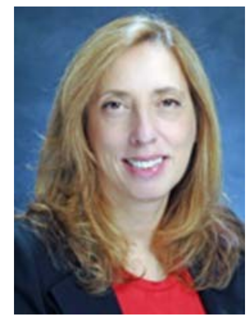
Chris Hansen
Self-healing materials

Steve Johnston
Product design/molding

David Kazmer
Machine design/control



Joey Mead
Elastomers/nano-materials

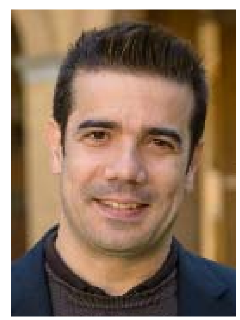


Nese Orbey
Structure-property relations

Ram Nagarajan
Biocatalysis/green polymers

Meg Sobkowicz-Kline
Rheology & renewable

Scott Stapleton
Modeling & textiles



Javier Vera-Sorroche
Extrusion & die design

David Willis
Computation fluid dynamics

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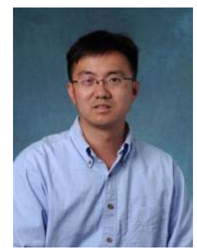

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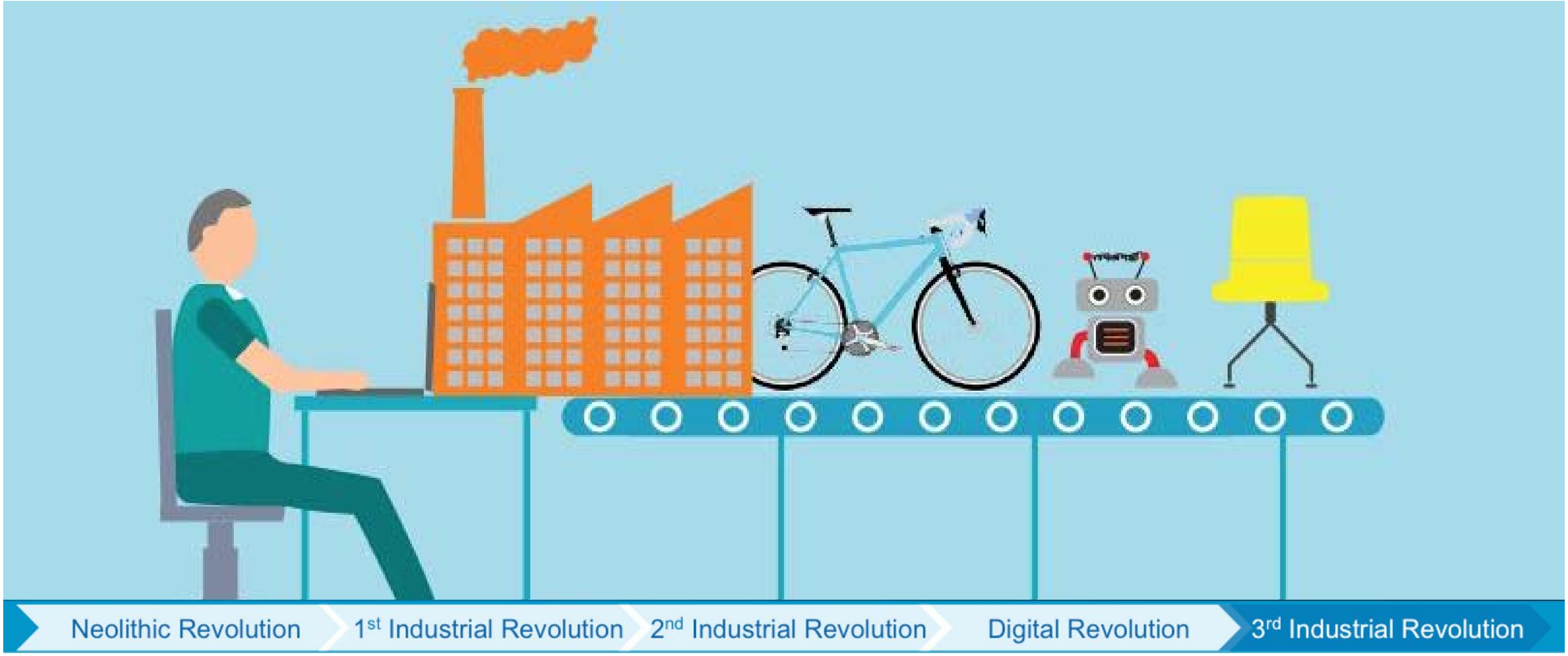
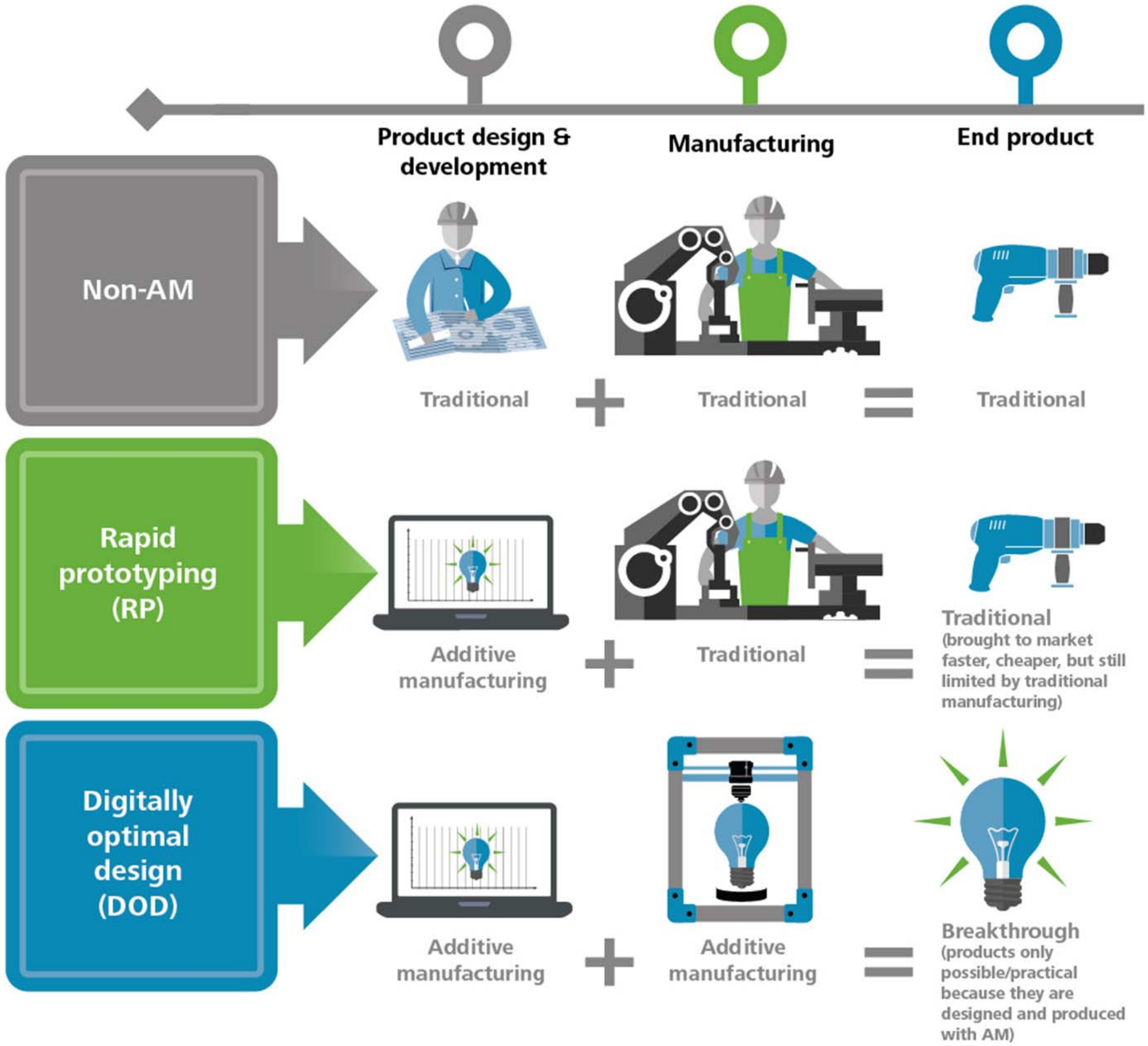
Future Trends



The 3rd Industrial Revolution

AM As Manufacturing



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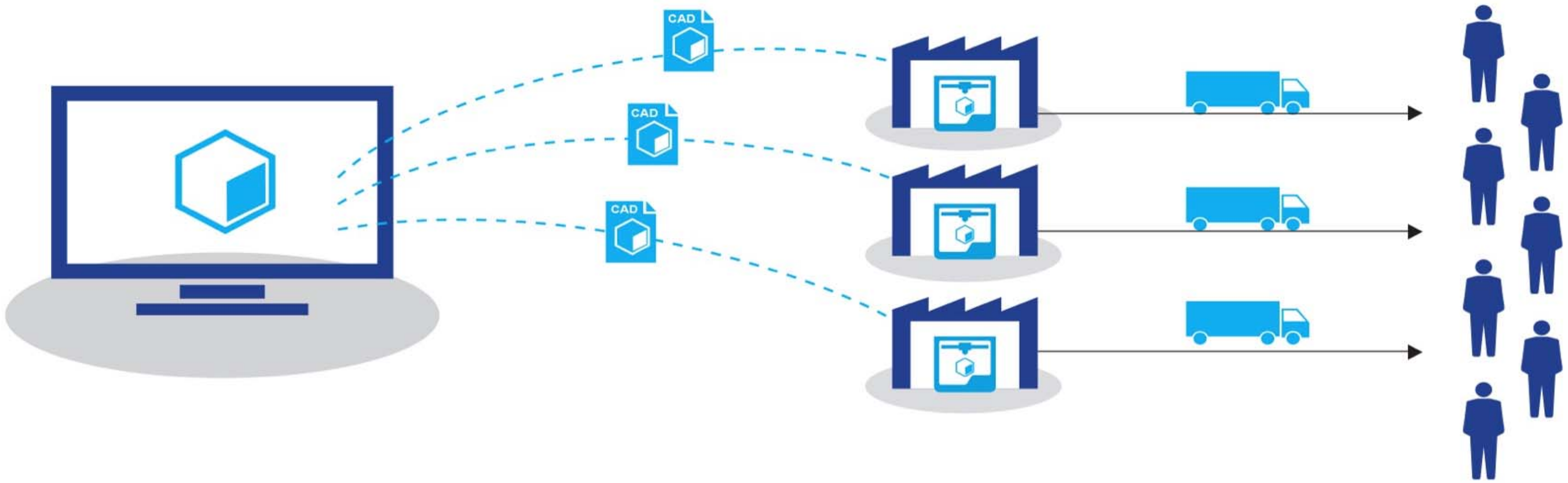
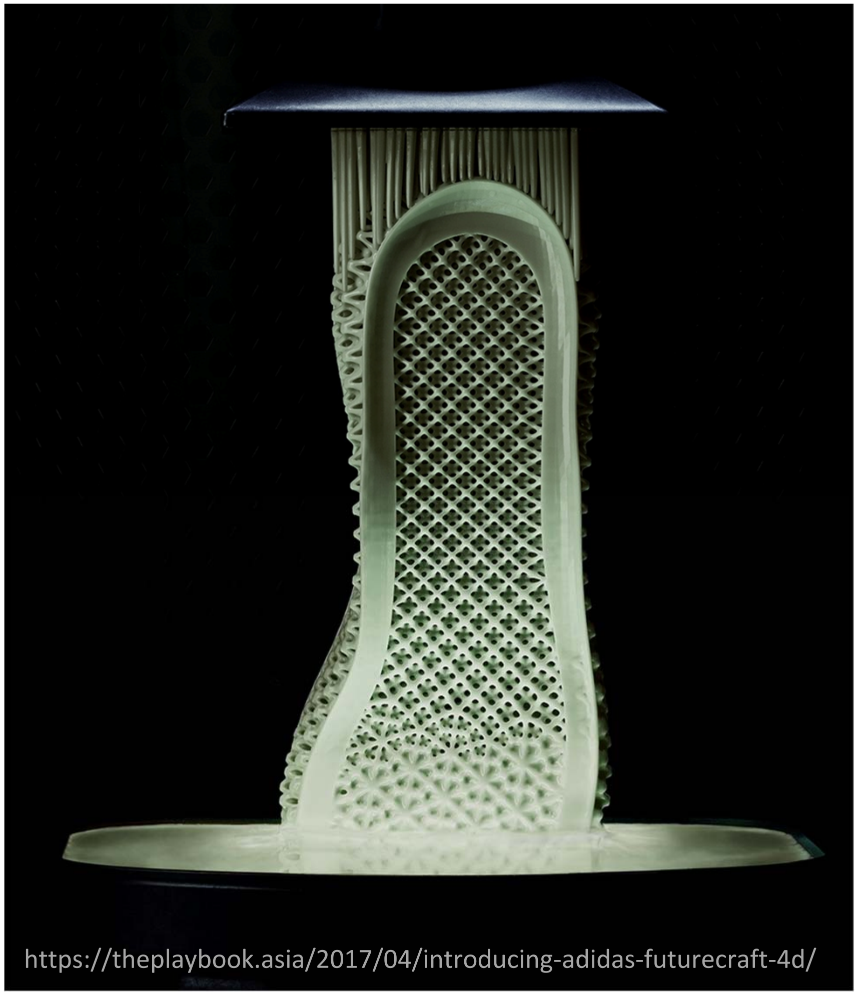
Factory of Tomorrow



Mass Customization



https://theplaybook.asia/2017/04/introducing-adidas-futurecraft-4d/

https://www.sculpteo.com/blog/2017/01/11/benefits-of-3d-printing-mass-customization/

New markets where customization comes low cost/free

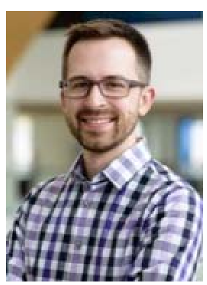
Closing Remarks

- *Current wave of manufacturing*: Additive manufacturing is a digital approach to manufacturing

- *Existing impact*: AM is HERE … and almost all industries are already using it!

- *Future impact*: As the technology evolves, the benefit for all industries will grow

Questions



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