UNIVERSITY OF ARKANSAS

AM³ Lab
Advanced Manufacturing | Modeling | Materials

Additive Manufacturing – Module 2

Spring 2015

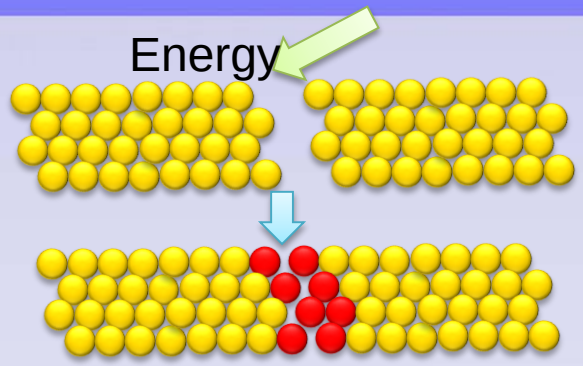
Wenchao Zhou

zhouw@uark.edu

(479) 575-7250

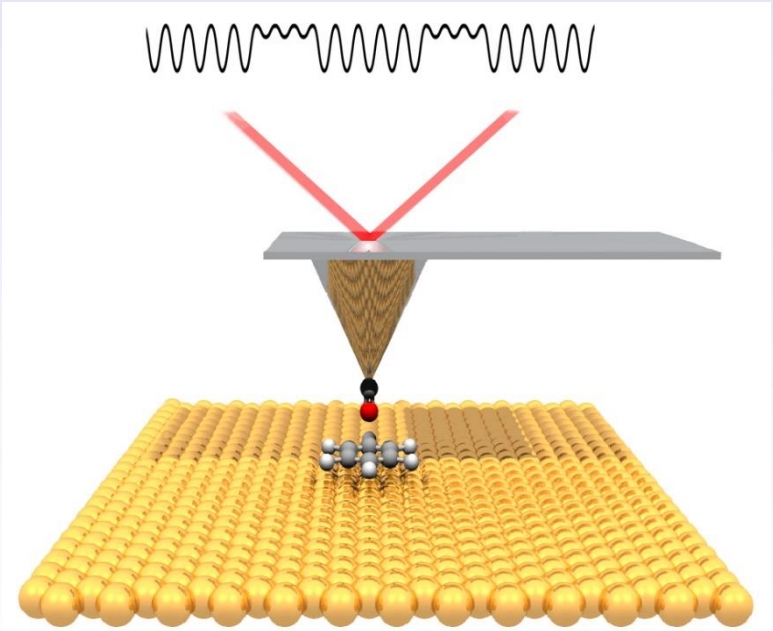
The Department of Mechanical Engineering
University of Arkansas, Fayetteville

What is AM



Additive: reducing material interface between material particles

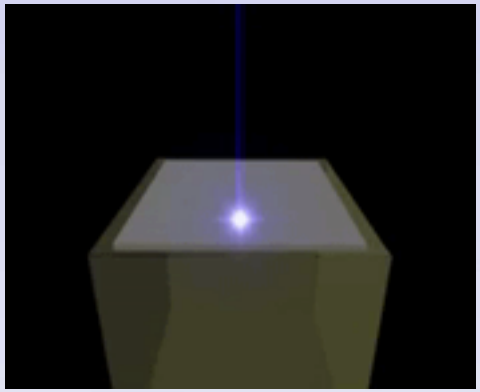
Lego



Build atom by atom, bond by bond

- **Material units (atom, droplets, powder particles, etc.)**
- **Bonding/joining mechanism (need to form new bonds between material units)**
- **Controlled (forming new bonds in a controlled fashion)**
- **Source of control (pattern energy or materials or both)**

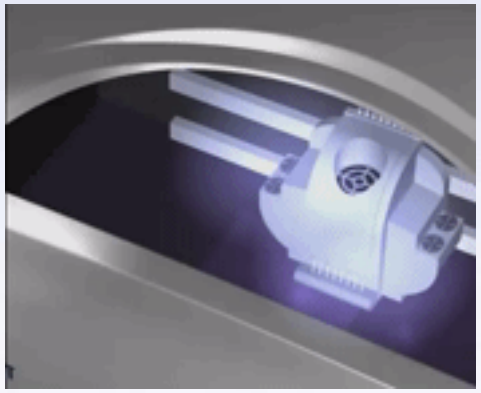
What is AM



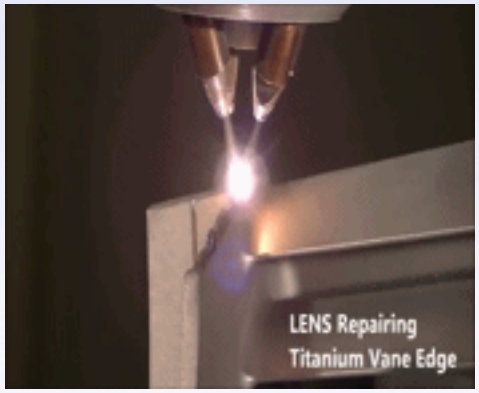
Stereolithography

Selective Laser Melting
Powder bed fusion processes

Fused Deposition Modeling
Extrusion based processes



Inkjet deposition
Printing based processes



Laser Engineered Net
Shaping Beam deposition
processes

Laminated Object
Manufacturing Sheet
lamination processes

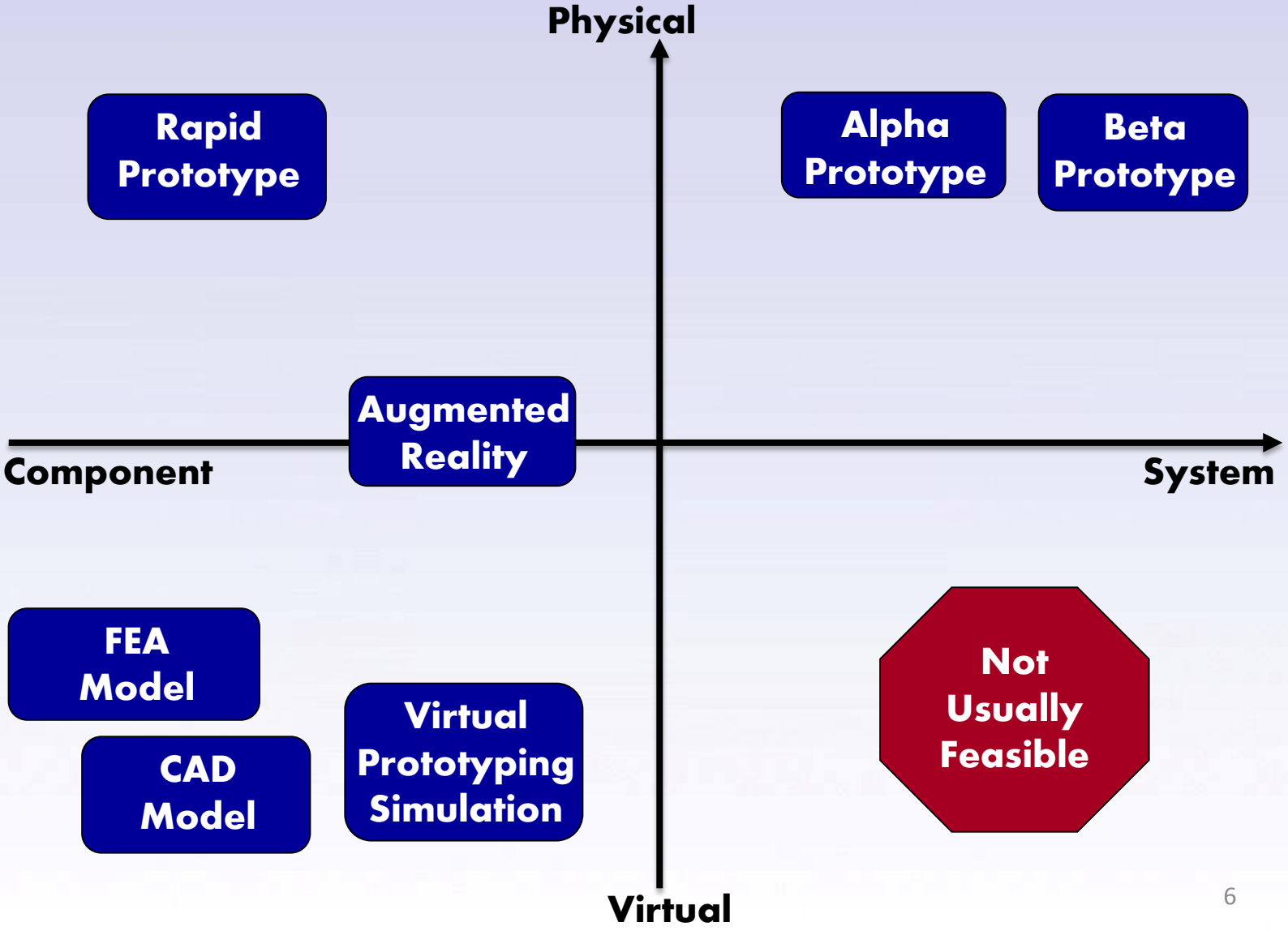
What is AM

- Stereolithography (SLA) - 3D Systems
- Selective Laser Sintering (SLS) - 3D Systems, EOS
- Fused Deposition Modeling (FDM) - Stratasys
- 3D Printing Technology (3DP) - Z Corp. (now 3D Systems), Ex One
- Inkjet - 3D Systems; Objet, Solidscape (now both Stratasys)
- Laser Engineered Net Shaping (LENS) – Optomec
- Direct Metal Deposition (DMD) – POM Group
- Solid Ground Curing (SGC) Cubital (out of business 2000)
- Ultrasonic Consolidation (UC or UAM) – Solidica (Fabrisonic)
- Laminated Object Manufacturing (LOM) – Helisys (Now Cubic Tech) & MCOR

What is AM

	1D	2D
	Point Scanning	**Area Filling**
Pattern Material	**FDM**	• **Inkjet (binder or material)** • **LOM** • **Ultrasonic Consolidation**
Pattern Energy	• **Stereolithography** • **Selective Sintering (laser or E-beam)** • **Selective Melting** • **LCVD (Georgia Tech)** • **Electrochemical Deposition**	• **Micro-SL with DMD (or DLP)** • **Solid Ground Curing**
Pattern Both	**LENS/DMD**	

Prototyping – Types of prototypes



Applications

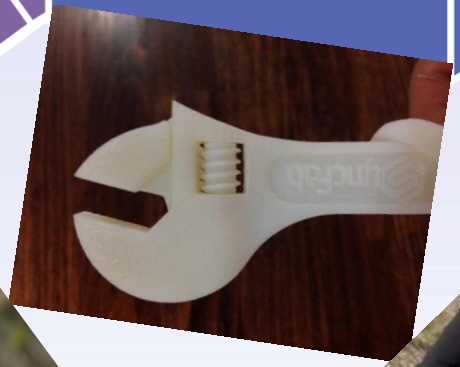
Prototyping – Design Applications

- Visualization
- Communication
- Marketing

Concept Models

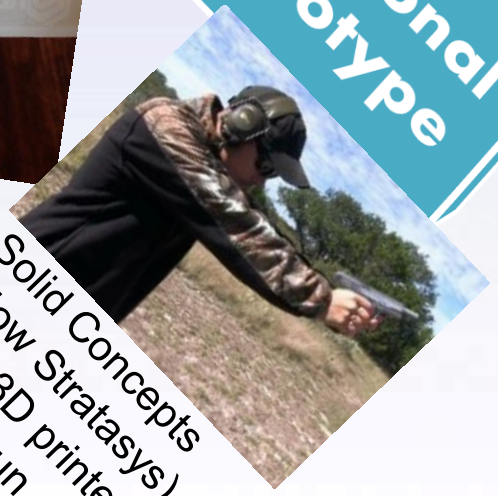
- Feel
- Assembly
- Motion/functions

Form-fit Models



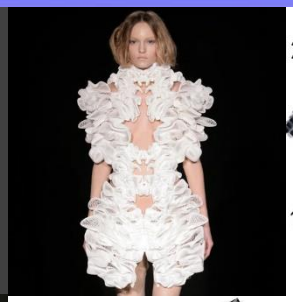
- Subject to testing

Functional Prototype

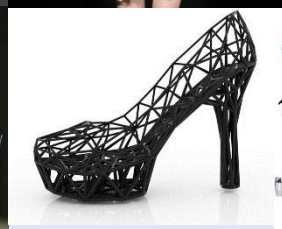


Solid Concepts (Now Stratasys), First 3D printed Metal Gun, 2013

Applications



Aerospace (parts & repairing)



Art, Fashion, Jewelry

Hearing aid - Siemens

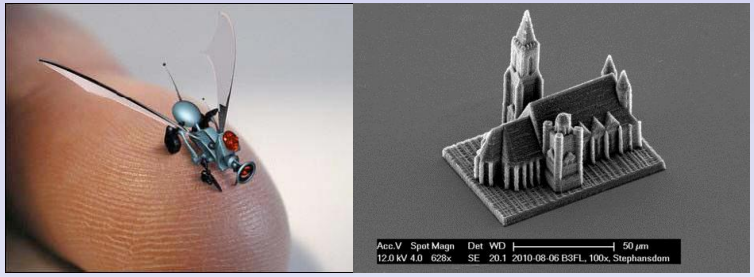
Align Technology

Automotive (RP & tooling)

Skull implants, 2011, by Xilloc Medical

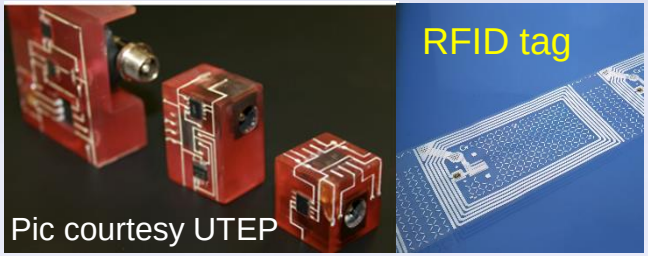
enablingthefuture.org

Prototyping – Design Applications



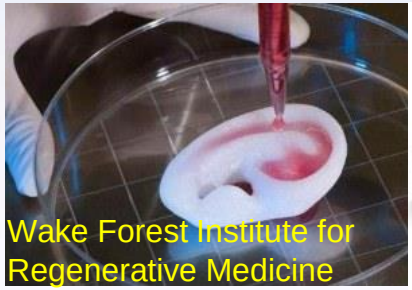
3D nano-printing

Food



Printed electronics (structural electronics, lightweight, integrated)

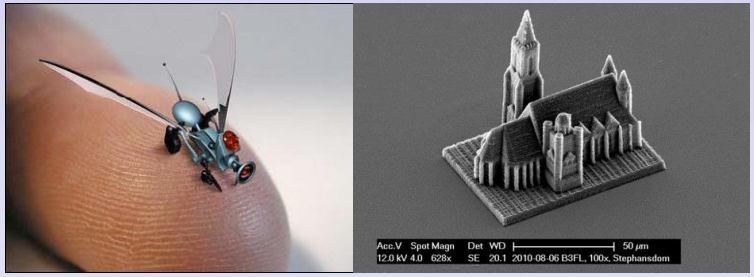
Entertainment (movie, Holywood)



Bioprinting

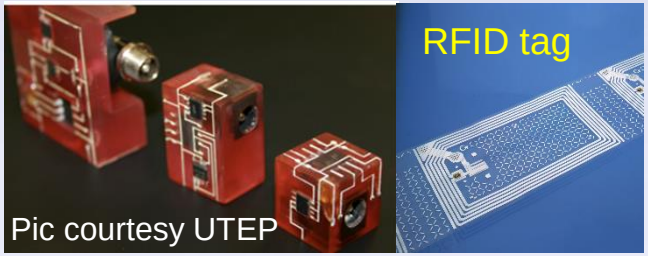
Education

Prototyping – Design Applications



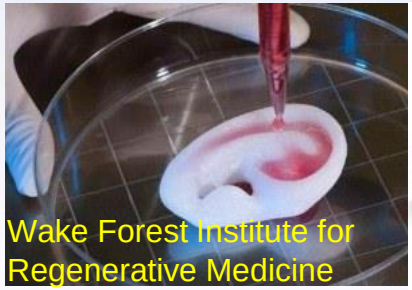
3D nano-printing

Food



Printed electronics (structural electronics, lightweight, integrated)

Entertainment (movie, Holywood)

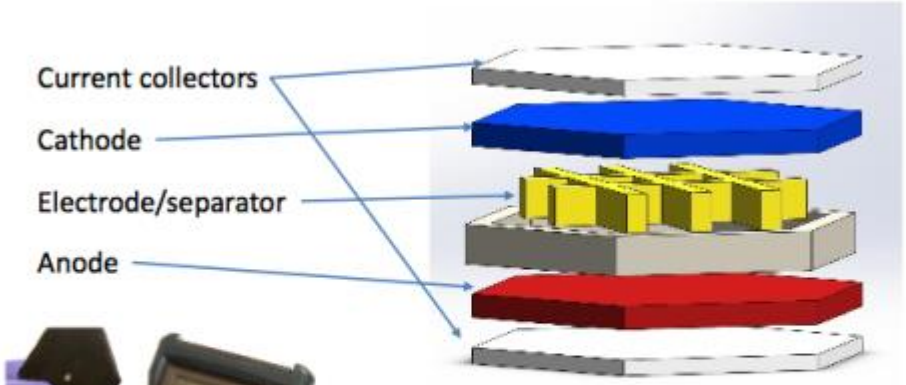


Bioprinting

Education

Applications

Emerging Technology: 3D Printed Battery

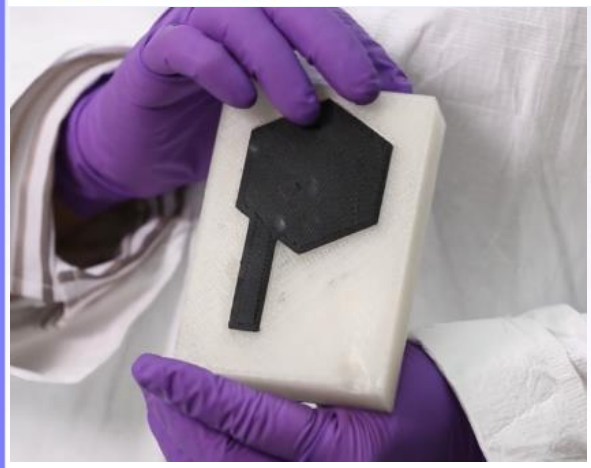


Working prototype

Our **unique** proprietary technologies are used to formulate materials for making each part of a battery by 3D printing

Courtesy Graphene 3D Lab

Need **MORE KILLER** Apps



Energy devices (battery, supercapacitors)

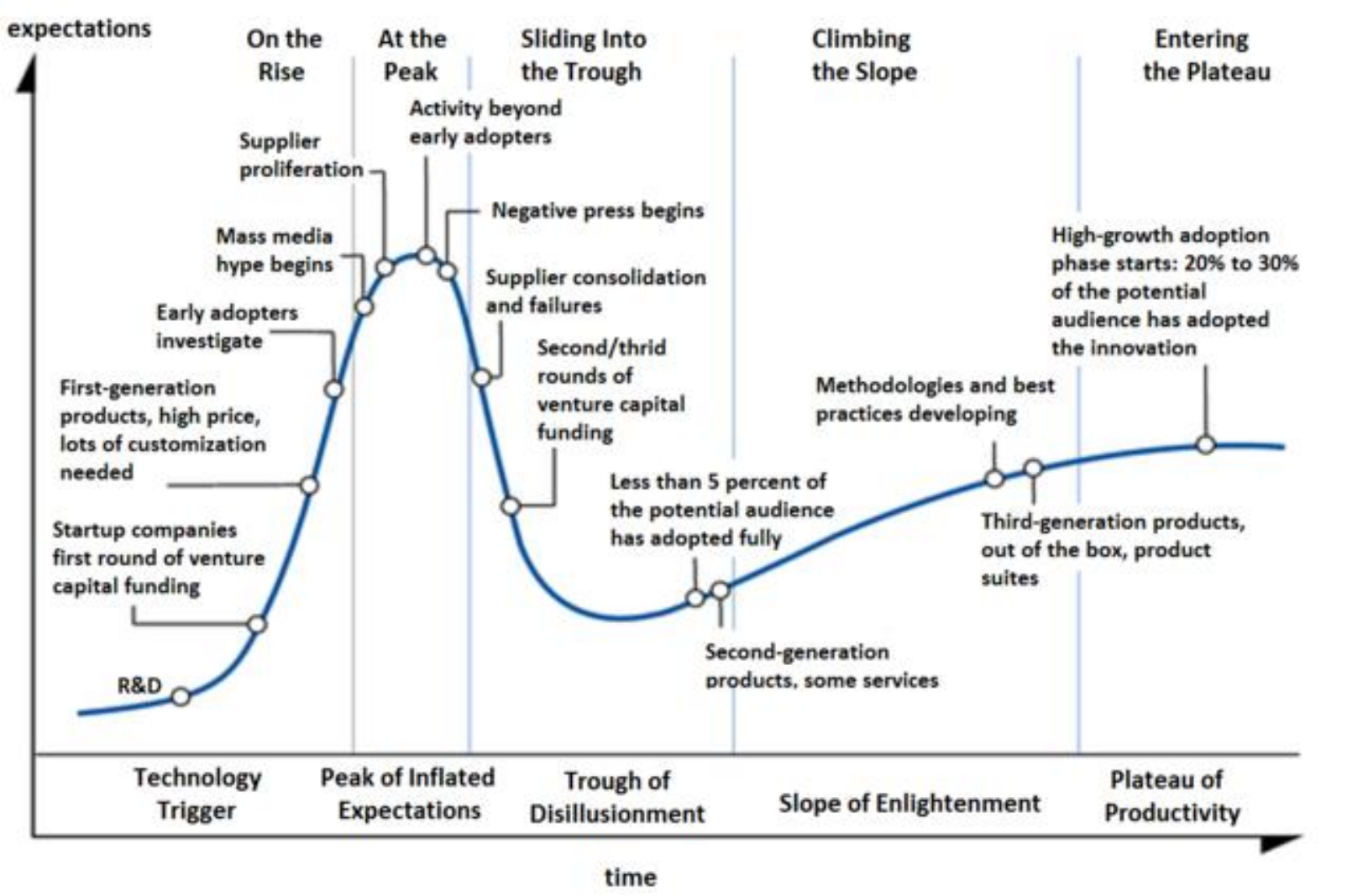
Applications

Need **MORE KILLER** Apps

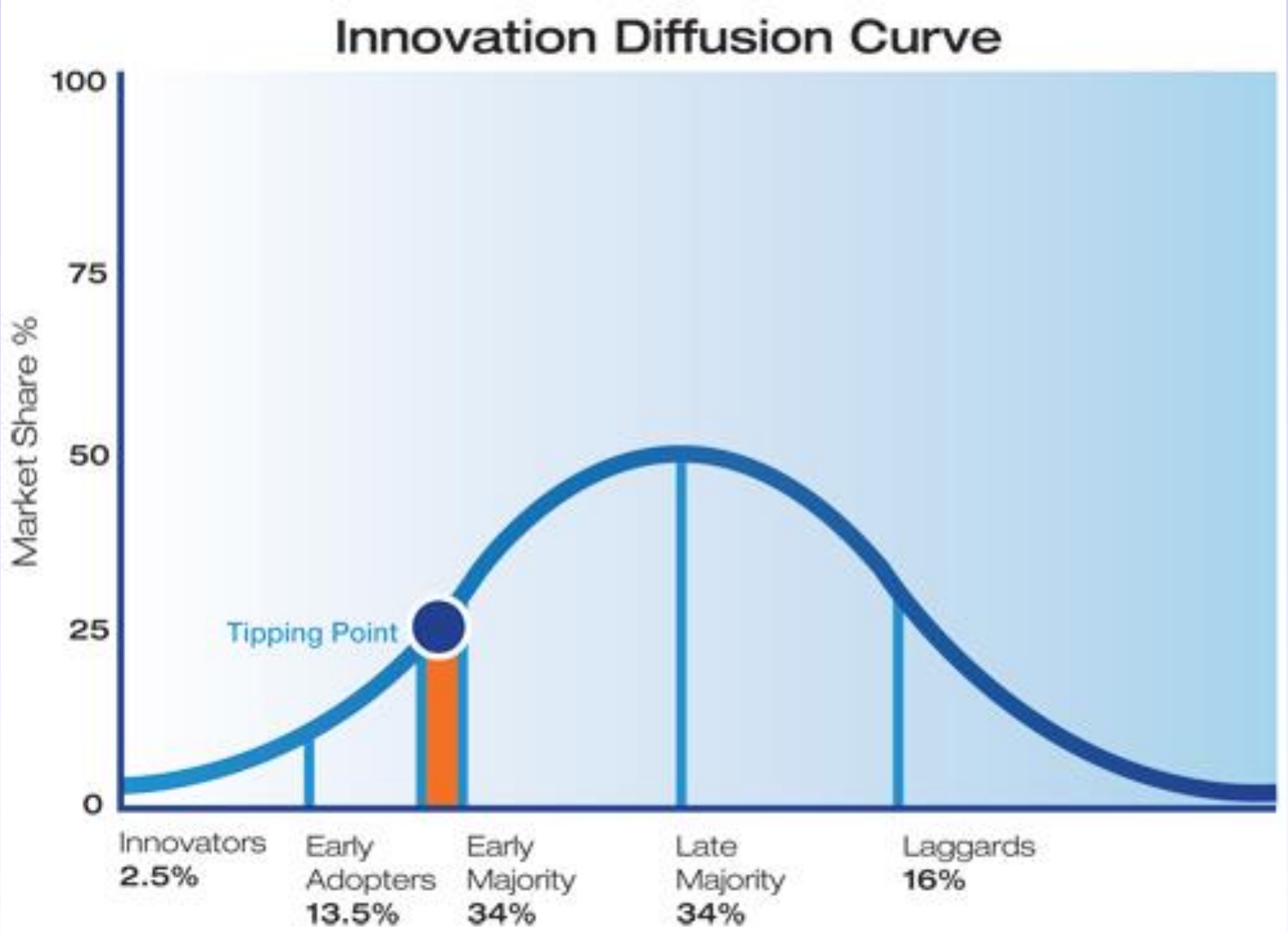
WinSun New Materials, Ma Yihe, Printing 10 homes in 24 hours
http://blogs.wsj.com/chinarealtime/2014/04/15/how-a-chinese-company-built-10-homes-in-24-hours/

Applications

- What is AM
- Applications
- How does it work
- Advantages
- Opportunities
- Challenges
- AM Industry

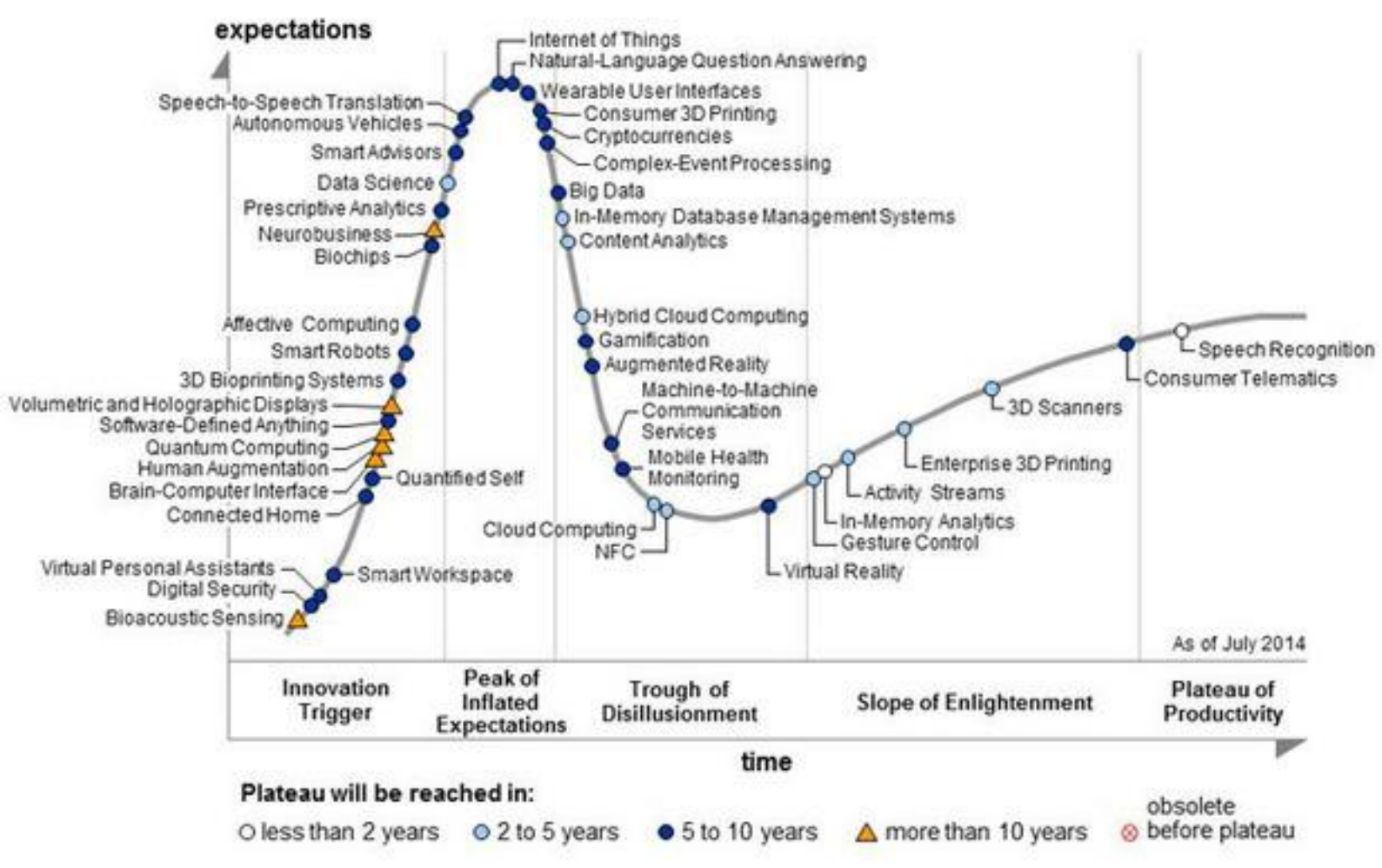


Applications

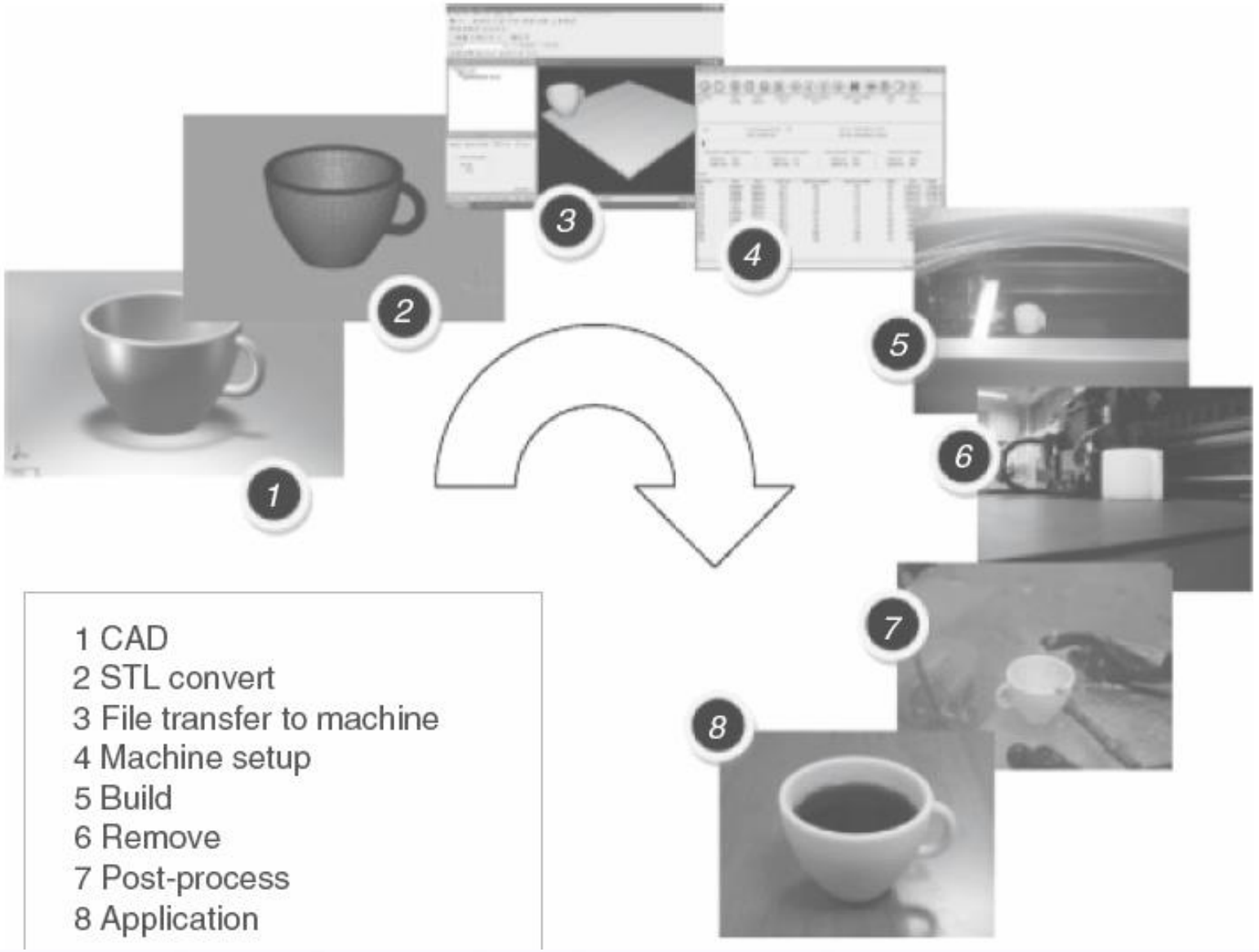


Applications

- What is AM
- Applications
- How does it work
- Advantages
- Opportunities
- Challenges
- AM Industry



How does it Work



1 CAD
2 STL convert
3 File transfer to machine
4 Machine setup
5 Build
6 Remove
7 Post-process
8 Application

How does it Work

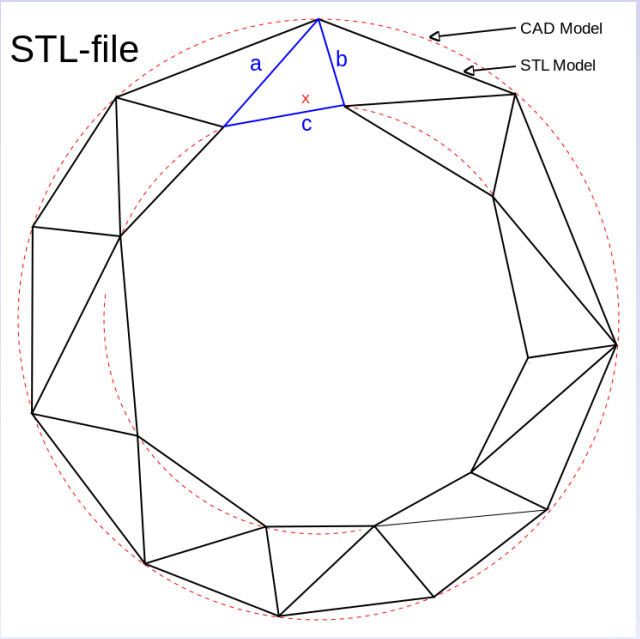
File Format – STL

```
solid name

facet normal ni nj nk
    outer loop
        vertex v1x v1y v1z
        vertex v2x v2y v2z
        vertex v3x v3y v3z
    endloop
endfacet

facet normal ni nj nk
    outer loop
        vertex v1x v1y v1z
        vertex v2x v2y v2z
        vertex v3x v3y v3z
    endloop
endfacet
.
.
.
endsolid name
```

Triangular "Soup"



Developed by 3D Systems: quasi-industrial standard
Name from the original technology: STereoLithography
ASCII or Binary format exist

Information Missing:

- **Color (Some systems added, e.g., VisCAM)**
- **Materials**
- **Process parameters**

How does it Work

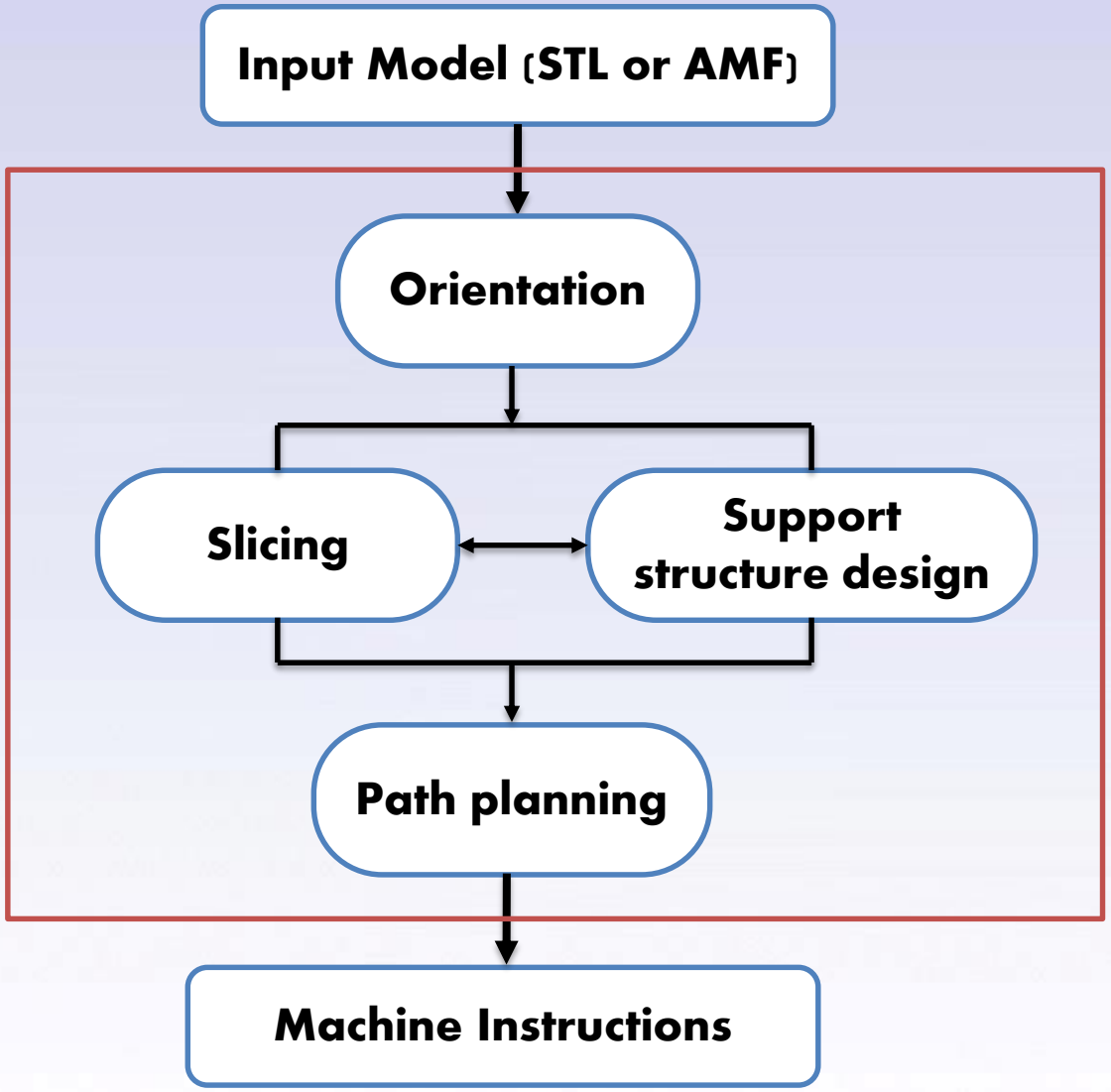
File Format – AMF

```
<?xml version="1.0" encoding="utf-8"?>
<amf unit="inch" version="1.1">
  <metadata type="name">Split Pyramid</metadata>
  <metadata type="author">John Smith</metadata>
  <object id="1">
    <mesh>
      <vertices>
        <vertex><coordinates><x>0</x><y>0</y><z>0</z></coordinates></vertex>
        <vertex><coordinates><x>1</x><y>0</y><z>0</z></coordinates></vertex>
        <vertex><coordinates><x>0</x><y>1</y><z>0</z></coordinates></vertex>
        <vertex><coordinates><x>1</x><y>1</y><z>0</z></coordinates></vertex>
        <vertex><coordinates><x>0.5</x><y>0.5</y><z>1</z></coordinates></vertex>
      </vertices>
      <volume materialid="2">
        <metadata type="name">Hard side</metadata>
        <triangle><v1>2</v1><v2>1</v2><v3>0</v3></triangle>
        <triangle><v1>0</v1><v2>1</v2><v3>4</v3></triangle>
        <triangle><v1>4</v1><v2>1</v2><v3>2</v3></triangle>
        <triangle><v1>0</v1><v2>4</v2><v3>2</v3></triangle>
      </volume>
      <volume materialid="3">
        <metadata type="name">Soft side</metadata>
        <triangle><v1>2</v1><v2>3</v2><v3>1</v3></triangle>
        <triangle><v1>1</v1><v2>3</v2><v3>4</v3></triangle>
        <triangle><v1>4</v1><v2>3</v2><v3>2</v3></triangle>
        <triangle><v1>4</v1><v2>2</v2><v3>1</v3></triangle>
      </volume>
    </mesh>
  </object>
  <material id="2">
    <metadata type="name">Hard material</metadata>
    <color><r>0.1</r><g>0.1</g><b>0.1</b></color>
  </material>
  <material id="3">
    <metadata type="name">Soft material</metadata>
    <color><r>0</r><g>0.9</g><b>0.9</b><a>0.5</a></color>
  </material>
</amf>
```

- Additive Manufacturing File
- ISO/ASTM Standard, 2011
- Machine independent (no layer or process information)
- XML-based format
  - <object>: volume of materials
  - <material>
  - <texture>
  - <metadata>
  - …

How does it Work

- Software pipeline – From model to machine instructions



- Orientation
- Support structure
- Slicing
- Path planning
- Machine instructions

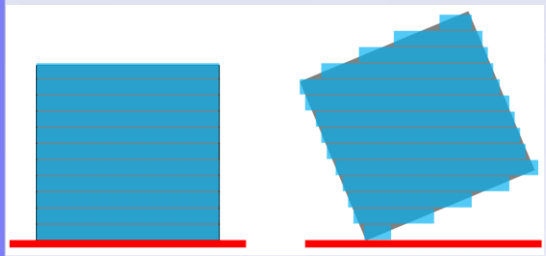
How does it Work

- **Orientation Determination**

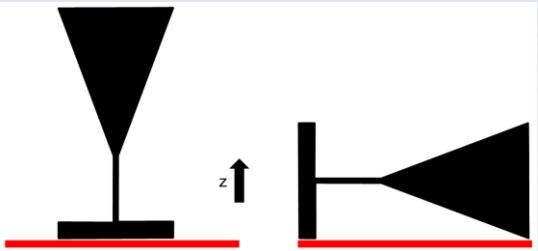
Factors

- **Surface accuracy**
- **Build time**
- **Support volume**
- **Support contact area**
- **Mechanical properties**

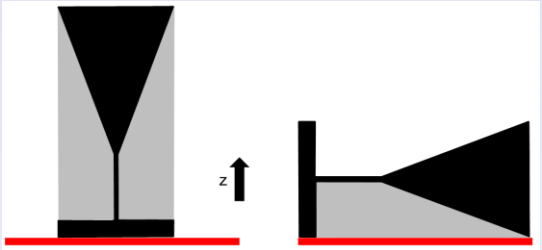
- **Orientation**
- **Support structure**
- **Slicing**
- **Path planning**
- **Machine instructions**



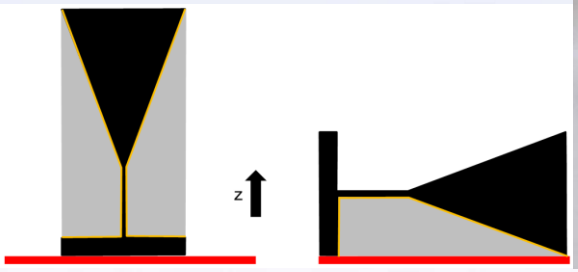
Surface accuracy



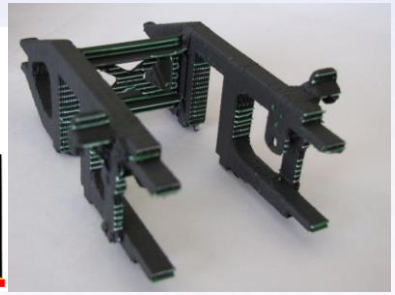
Build time



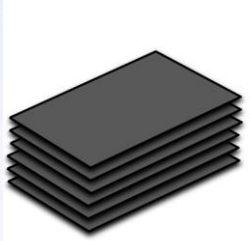
Support material volume



Support contact area



After support removal



Mechanical property (weaker in Z direction)

- Manual: user
- Semi-auto: user and software
- Auto: software

Courtesy Prof. Wojciech Matusik@MIT

How does it Work

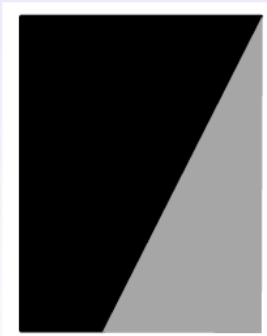
- **Support structure design**
  - **"Powder" bed based processes: Do NOT need support structures: SLS, SLM, etc.**
  - **Others DO: SLA, FDM, Inkjet deposition, etc.**

Objectives

- **Prevent curling due to internal stress**
- **Supporting overhangs**
- **Maintaining stability**

- **Orientation**
- **Support structure**
- **Slicing**
- **Path planning**
- **Machine instructions**

Empirical "rules"

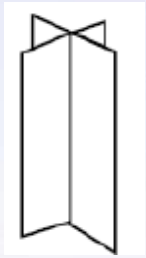


Inkjet

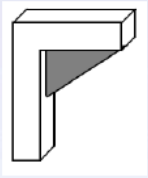
FDM (up to 45 degrees)

Support types

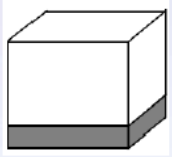
Column (SLA)



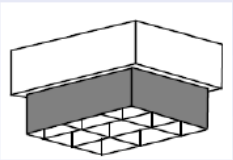
Gusset



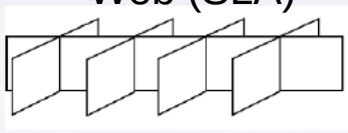
Base



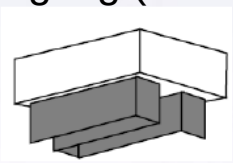
Perimeter&hatch



Web (SLA)



Zigzag (FDM)



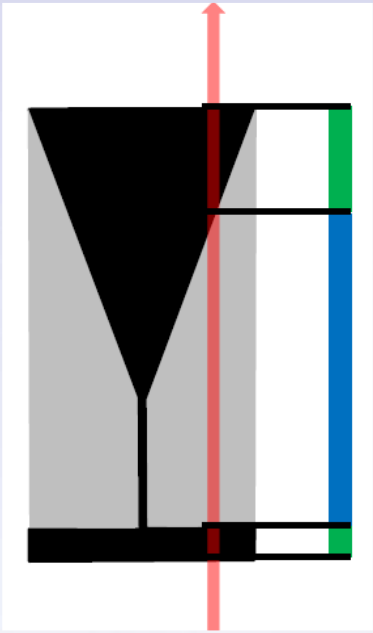
Courtesy Prof. Wojciech Matusik@MIT

How does it Work

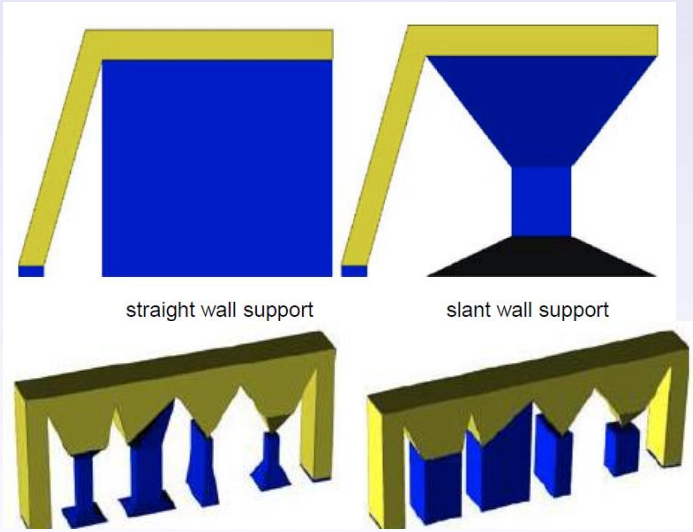
- **Support structure design**

Algorithms for generating support structures

- **Simple ray casting algorithm**



- **Orientation**
- **Support structure**
- **Slicing**
- **Path planning**
- **Machine instructions**



Optimized VS unoptimized

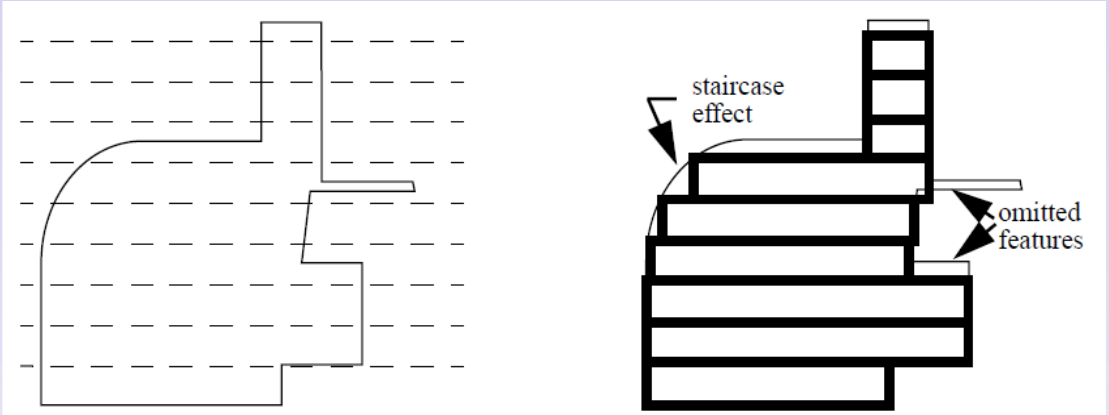
Advanced algorithms

- **Minimize the use of support material**
- **Or for other purposes, such as minimize curling**

Courtesy Prof. Wojciech Matusik@MIT

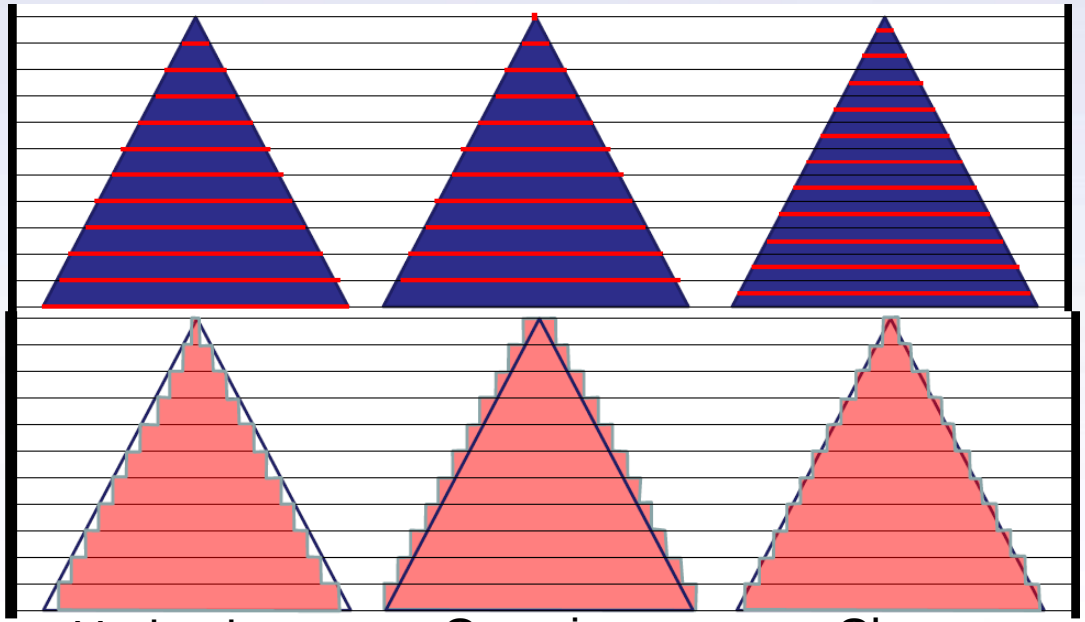
How does it Work

- **Slicing**



- **Orientation**
- **Support structure**
- **Slicing**
- **Path planning**
- **Machine instructions**

For each z, compute intersection of a plane with the model



Courtesy Prof. Wojciech Matusik@MIT

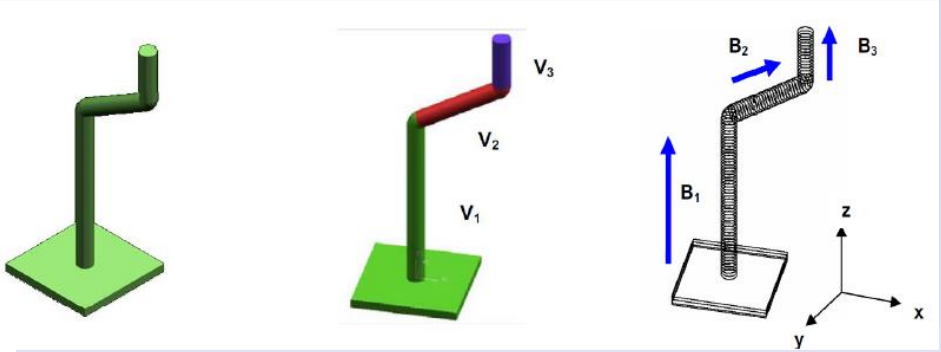
How does it Work

- **Slicing**

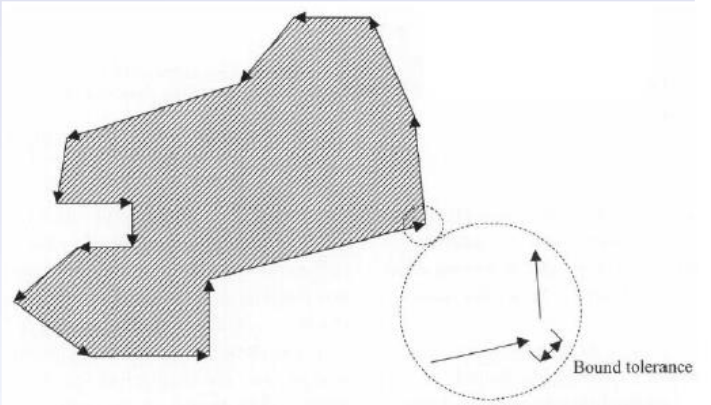
Many research on slicing

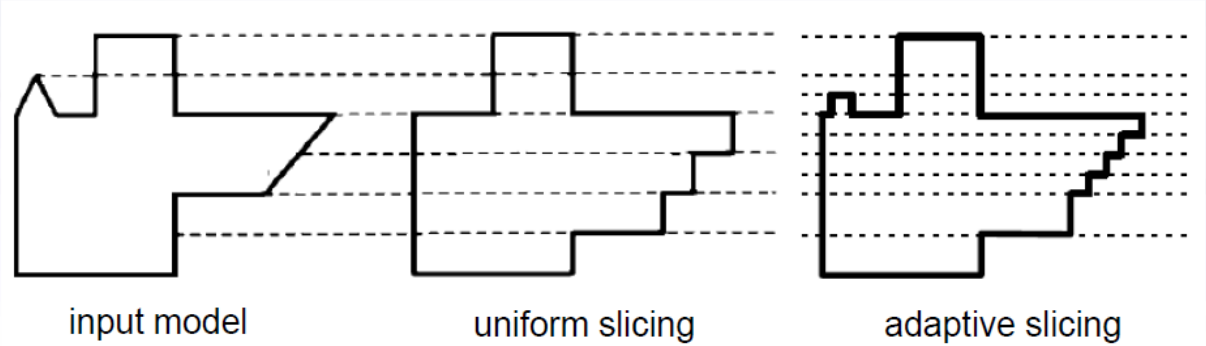
Slicing STL

- **Voxelization (determine inside or outside)**
- **Then extract contours**
- **Epsilon issues (machine precision)**



Multi-direction slicing





Adaptive slicing

Courtesy Prof. Wojciech Matusik@MIT

How does it Work

- **Path planning**

Two types

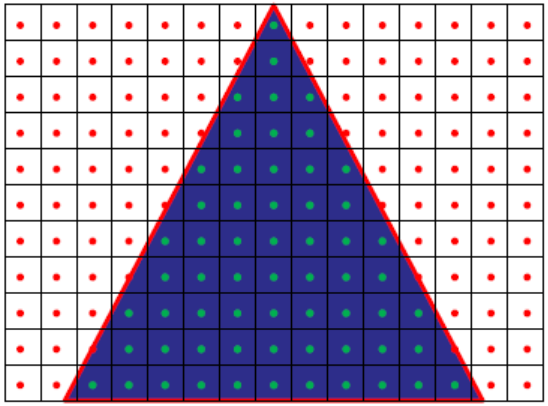
- 2D (area filling at once): raster-based
- 1D scanning tool path: vector-based

Factors

- Surface accuracy
- Build time
- Mechanical properties: stiffness, strength, distortion

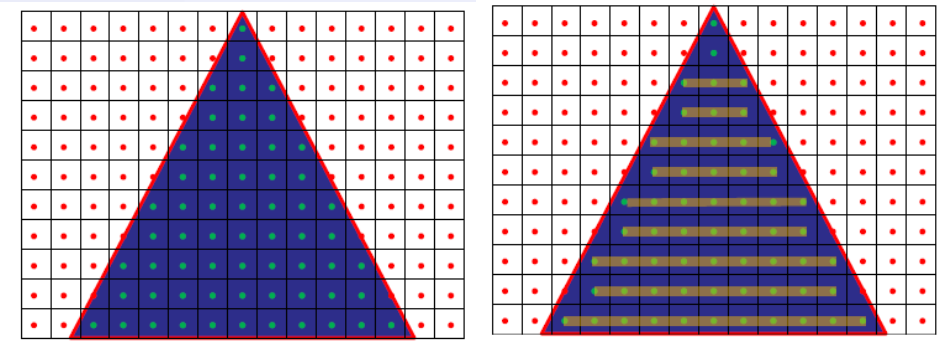
- Orientation
- Support structure
- Slicing
- Path planning
- Machine instructions

For raster-based: e.g., inkjet



After voxelizaton, superimpose a voxel grid

For vector-based: e.g., SLA



1. Superimpose a voxel grid
2. Rows and columns used as tool paths

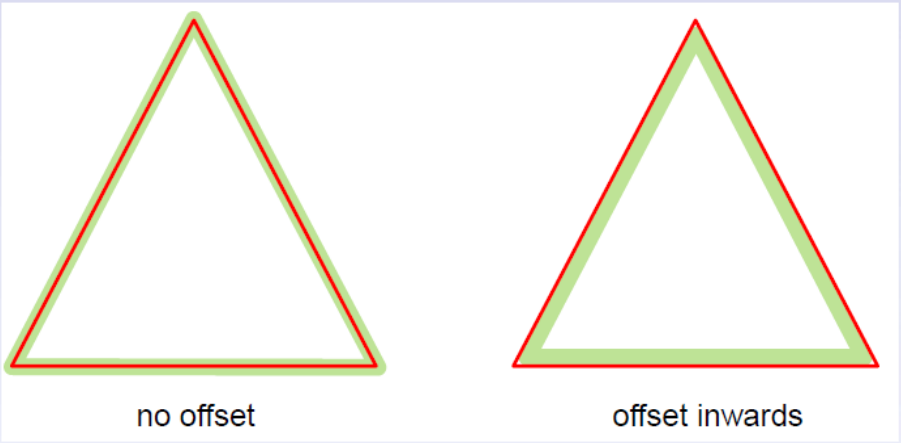
Courtesy Prof. Wojciech Matusik@MIT

How does it Work

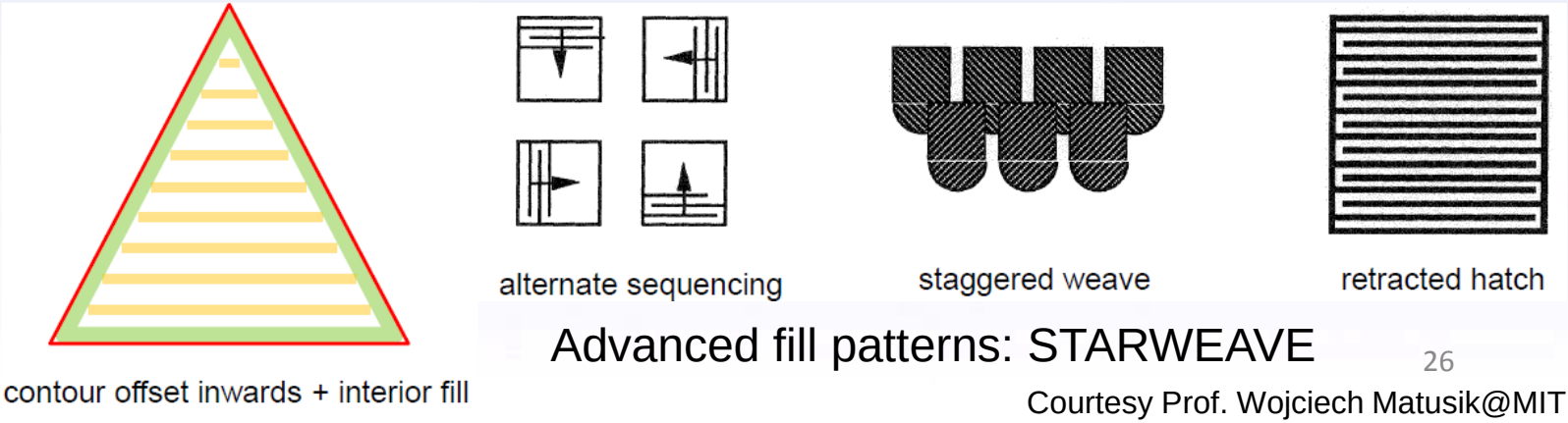
- **Path planning**

For vector-based

- **Tracing contours: improved surface accuracy**



- **Tracing contours + filling interiors**



- **Orientation**
- **Support structure**
- **Slicing**
- **Path planning**
- **Machine instructions**

Advanced fill patterns: STARWEAVE

Courtesy Prof. Wojciech Matusik@MIT

How does it Work

- **Machine Instructions**
  - **Raster-based, e.g., inkjet: proprietary, can be exported as image files (PNG, BMP, etc.)**
  - **Vector-based, e.g., FDM:**
    1. **G-code (dominant);**
    2. **SLI by 3D Systems**

- **Orientation**
- **Support structure**
- **Slicing**
- **Path planning**
- **Machine instructions**

G-Code

- **Developed at MIT in 1950s for CNC milling**
- **Simple instructions telling machine**
  - **where to move**
  - **how fast to move**
  - **what path to move**

Sample instructions:

-**G00: Rapid move**

•does not necessarily move in a single straight line between start point and end point. It moves each axis at its max speed until its vector is achieved.

-**G01: Linear interpolation**

•specify the start and end points, and the control automatically calculates the intermediate points to pass through that will yield a straight line

-**G02: Circular interpolation, clockwise**

Courtesy Prof. Wojciech Matusik@MIT

How does it Work

- **Post-processing – depends on process**

  Steps:
  - **Remove the part from the build platform and depowder (if powder based) and cleaning;**
  - **Remove the support structures from the part using appropriate tools**
  - **Post-curing (SLA)**
  - **Surface finishing**

- **Example of SLA**

Remove build platform and the part

Rinse in IPA

Remove supports

Finish w. sand paper and mineral oil

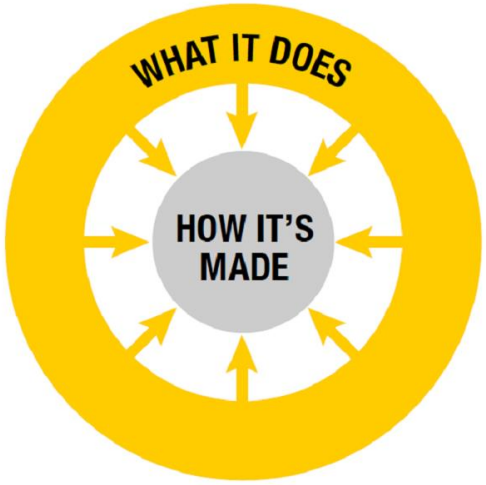
Animations from Formlabs

Advantages

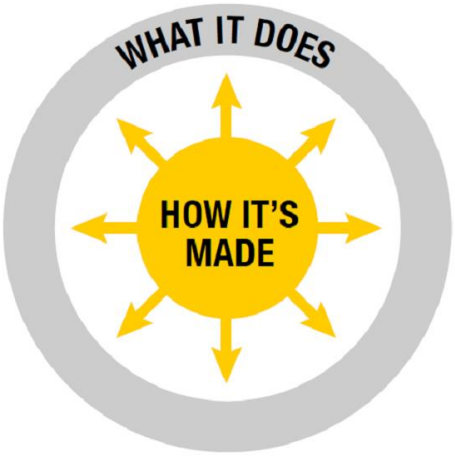
Design Freedom

Complexity is nearly free
- Geometry
- Material
- System

Pic Credit: Fathom

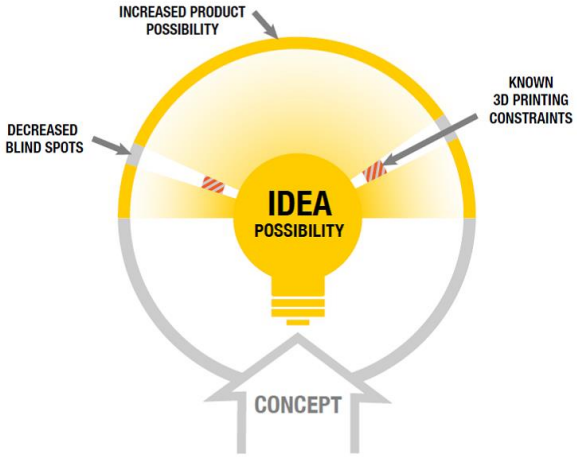


ADDITIVE MFG
Drives Innovation

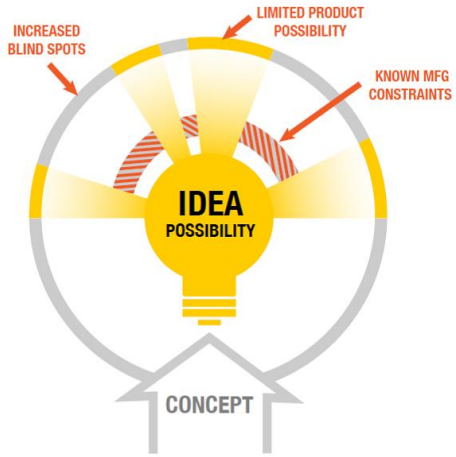


TRADITIONAL MFG
Limits Design

DESIGN FREEDOM: Increase Product Possibility



ADDITIVE MFG
Increase Design Possibility
with Minimal Blind Spots and Constraints



TRADITIONAL MFG
Limits Design Possibilities
with Many Blind Spots and Constraints

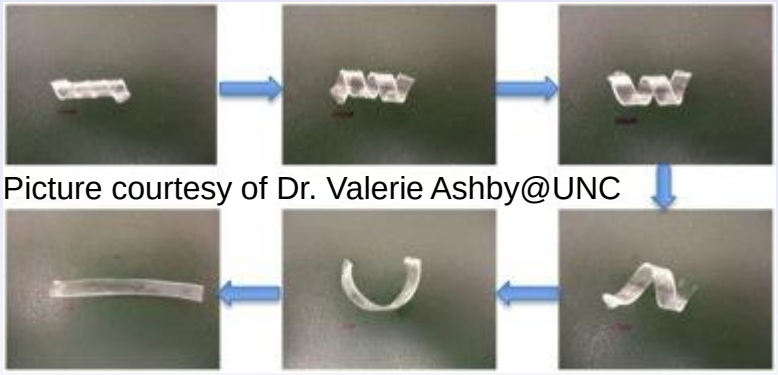
Advantages

- **Digital**

Opportunities

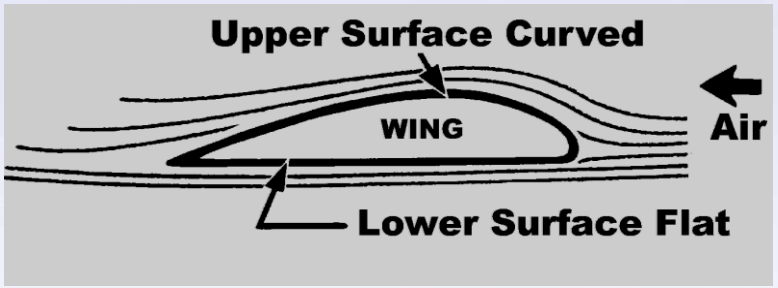
- **Integrated smart structures**
  - **Reduced volume and weight (make everything more "compact" and "wearable")**
  - **Smart: structures that can sense, communicate, respond, and process information; (no more "dead" structures)**

Mimosa



Picture courtesy of Dr. Valerie Ashby@UNC

Shape memory polymers – change structure at external stimulus



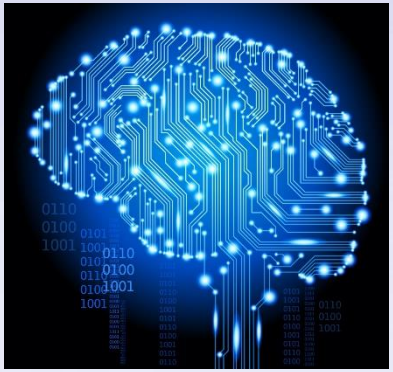
Design a wing structure that can adapt its shape to the environment

Imagine: a shoe that can change size, color, and shape

Opportunities

- **Blur the boundary between physical and digital world**
  - **Giving the autonomous producing capability to machines**
  - **Life: sense, information processing, responding (executing instructions), metabolism + autonomous reproduction**

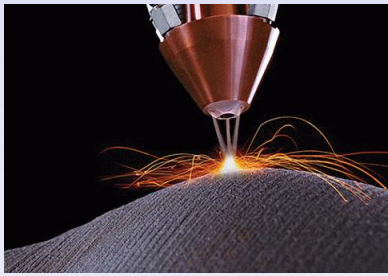
Robotics



Artificial Intelligence

Internet of things

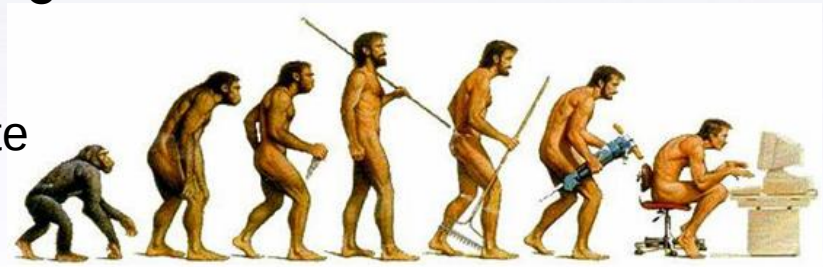
+



3D printing

A self-evolving world that doesn't need humans

Self-Repair
Self-Replicate
Self-Evolve



Opportunities

- What is AM
- Applications
- How does it work
- Advantages
- Opportunities
- Challenges
- AM Industry

- **Revolutionizing product value chain**

What we do now

Professional Design


Mass Production

Transportation


Local distribution

Shopping Mall

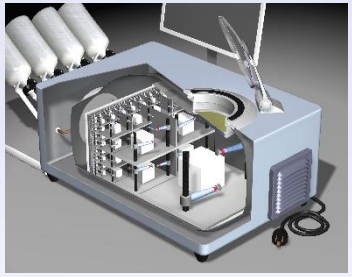
What we will do when we get there


Custom Design with Professional Design Software


Internet


Local Production Center with 3D Printers

OR


Desktop Factory

Need to digitalize most of our current products (we are currently only able to 3D print a negligible tiny portion of our current products)

Challenges

- **TOO Slow (<~1000 cm³/hr)**

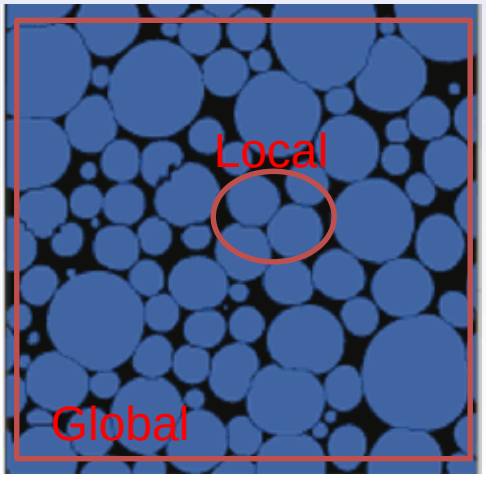
Build a house brick by brick

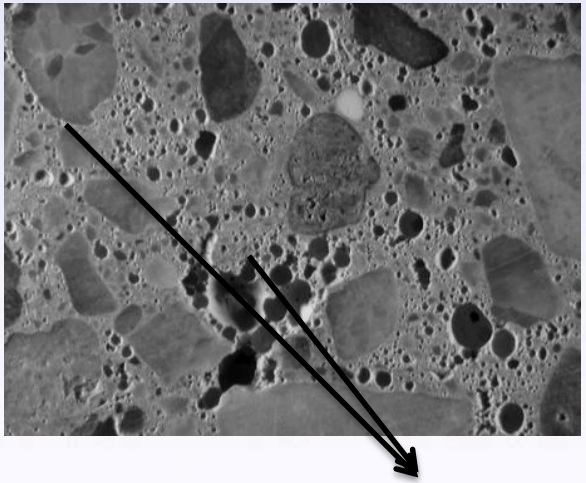
Parallel building – scaling up

- **Material unit volume (resolution^3) – use coarse resolution**
- **Deposition frequency (~10kHz) or scanning speed (<~1000 mm/s) – increase frequency to MHz + parallel building**
- **Delay between layers (<~1s) – continuous building**
- **Post-processing (~1x of build time) – eliminate it**

Challenges

- **Materials**
  - **Energy patterning**
    - **Common choices: photopolymer, thermoplastics, Titanium (alloys), steel;**
    - **Difficult materials: aluminum, ceramics, biomaterials, etc.**
  - **Material patterning (sensitive to material properties)**
    - **Viscosity (e.g., inkjet, < ~40cP)**
    - **Surface tension (e.g., syringe)**
- **Properties**





Voids/Material interfaces:
Lead to stress concentration, etc.

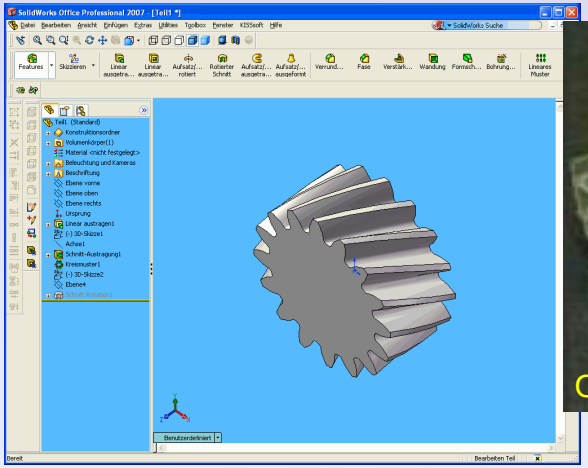
Core idea of AM: material joining (reduce material interfaces) → undesired material interfaces lead to inferior material properties

Challenges

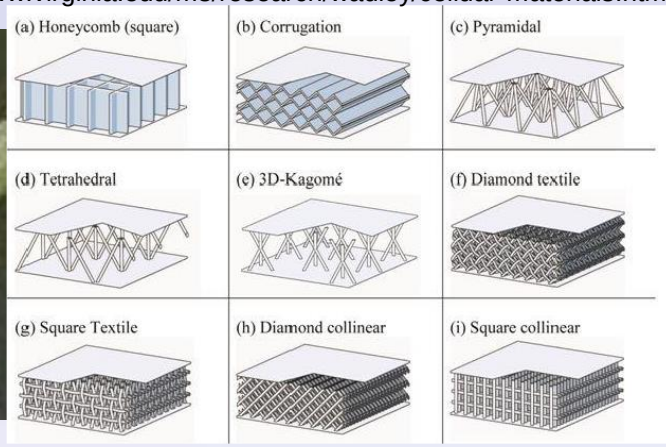
- What is AM
- Applications
- How does it work
- Advantages
- Opportunities
- Challenges
- AM Industry

- **Design complexity (Mutliscale & multi-resolution) from design freedom**
  - **Geometry**
  - **Material composition**
  - **Local process parameters (open loop, repeatability)**

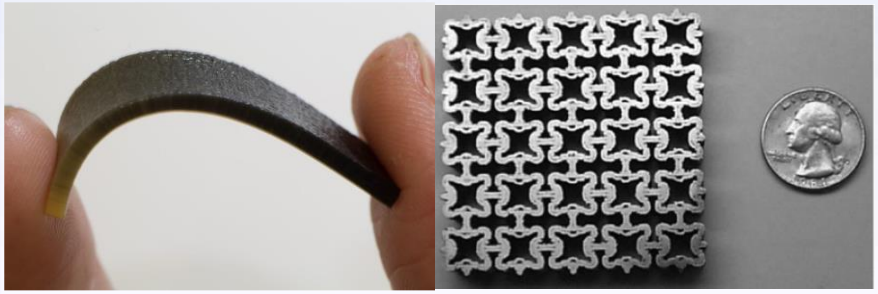
http://www.virginia.edu/ms/research/wadley/celluar-materials.html



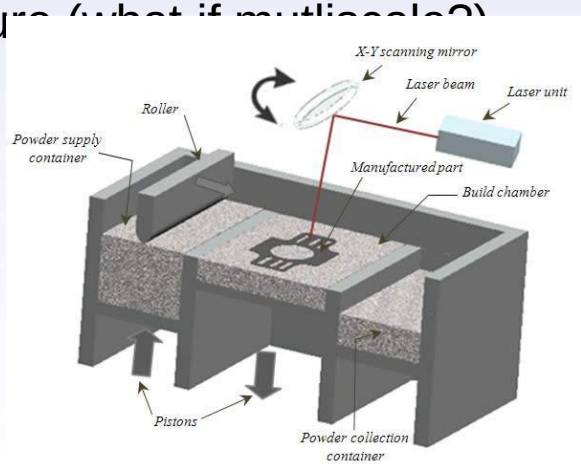
Current CAD system



Design and optimize lattice structure and cellular structure (what if mutliscale?)



Design of material composition (functional graded material, metamaterial)

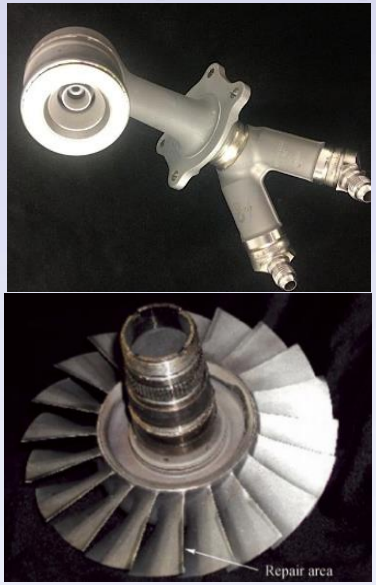


Local process parameters

Challenges

- What is AM
- Applications
- How does it work
- Advantages
- Opportunities
- Challenges
- AM Industry

- **Killer applications**
  - **Faster, cheaper, better solution for large-scale common & important problems**



Aerospace (multi-billion dollar industry)

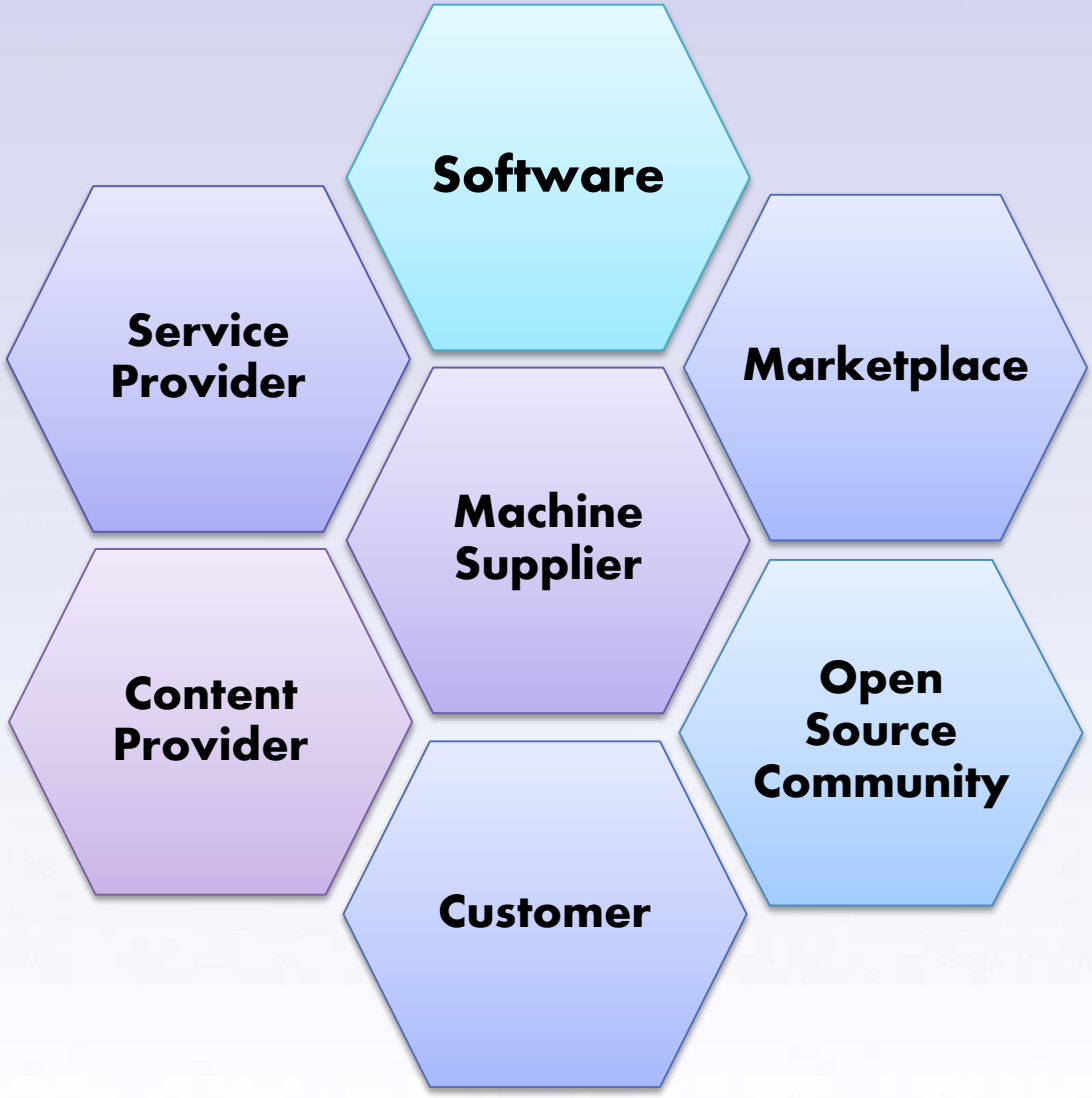
Align Technology (multi-billion dollar industry)

Need **MORE** SIMPLE IDEAS for better solutions

Printed RFID (multi-billion dollar industry)

Printed flexible display

AM Industry



AM Industry

- **3D Content Provider**

CAD

3D Scanners

Online Repositories

http://reprap.org/wiki/Printable_part_sources

- **Marketplace (Share, buy, and sell designs)**

Sell prints

Sell design files

Sell both

Search engine

http://makingsociety.com/2013/07/37-3d-printing-marketplaces-to-share-buy-and-sell-3d-designs/

AM Industry

- What is AM
- Applications
- How does it work
- Advantages
- Opportunities
- Challenges
- AM Industry

3D Printing service

iMakr.com

makexyz

3D HUBS

Connect to local 3D printers (cloud)

Provide local store printing service

Quickparts

Stratasys FOR A 3D WORLD™

SOLID CONCEPTS

LayerWise

Paramount

ProtoCAM Excellence in Additive Manufacturing

http://www.wohlersassociates.com/service-providers.html

Solution providers (industrial)

AM Industry

- What is AM
- Applications
- How does it work
- Advantages
- Opportunities
- Challenges
- AM Industry

Machine suppliers

	Major Players	Materials
SLA	3D Systems, Stratasys, envisionTEC	**Photopolymers**
FDM	Stratasys, 3D Systems, Stratasys MakerBot Industries, RepRap	**Thermoplastics**
Inkjet	Objet, Stratasys, 3D Systems, Dimatix FUJIFILM, PiXDRO, MicroFab Technologies Inc.	**Photopolymer; Metal/ceramics in suspension**
Powder (bed)	CAD to Metal, Arcam AB, ExOne, Z Corporation, Renishaw, EOS e-Manufacturing Solutions, voxeljet, SLM Solutions GmbH, Phenix Systems, 3D Systems, HP, Optomec	**Powders: Metal, ceramics, plastic, glass, plaster, sand, etc.**

Optomec: Production Grade 3D Printers... with a Material Difference

AM Industry

- **Software (convert STL files to machine instructions)**

AUTODESK® MESHMIXER®
netfabb®
http://reprap.org/wiki/Useful_Software_Packages
Materialise innovators you can count on
Craft Unique
Skeinforge
Slic3r G-code generator for 3D printers
AutoFab R&D
Magics by Materialise
SIMPLIFY3D™
Cura
MESHLAB IL SOFTWARE ITALIANO PER CREARE MODELLI 3D

Closed source

Open source

- **Material suppliers**

Applied Graphene Materials
Carestream Advanced Materials
AGFA Agfa
3Dfilamenta.com
Bucktown Polymers
GIZMODORKS
DSM BRIGHT SCIENCE. BRIGHTER LIVING.
intrinsiq materials
CONDUCTIVE COMPOUNDS Innovative Chemistry for High-Tech Applications
PRINTSPACE
ESSTECH, Inc.
AZ Electronic Materials
DUPONT
Arevo PERFECTING THE ART OF 3D PRINTING
spot-A materials
ANP Advanced Nano Products
RMI Rieke Metals, Inc.

Filaments | Photopolymers | Printable inks

http://www.additive3d.com/mat_lks.htm http://reprap.org/wiki/Printing_Material_Suppliers

AM Industry

Customers

Aerospace & Defense

Architecture & Geo

Automotive

Education

Energy

Healthcare

Jewelry

Hobbyist

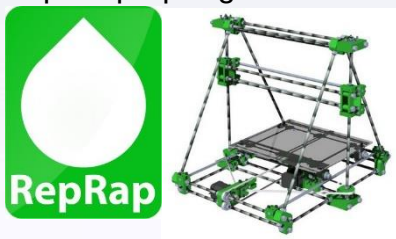
Consumer

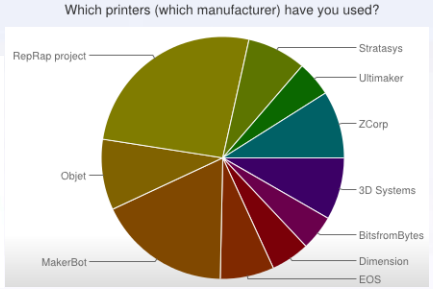
http://www.3dsystems.com/solutions/overview

Open source community

http://reprap.org/

Evan Malone and Hod Lipson Cornell, 2006, syringe based (dying after 2012)





Adrian Bowyer, U of Bath, UK; Self-replicating, FFF based, Arduino-based control, Thriving