# Achieving Higher Level Data Interoperability with 3D Printing


Sally Chan
Associate Technical Fellow

# Biography



- **Education**
  - B.A. UCLA Design
  - M.A. UCLA Computer Aided Design
  - Certificate Program
    - UCLA eBusiness
    - Penn State Univ. Graduate Enterprise Architecture
    - MIT 3D Printing/Additive Manufacturing
  - License – Private Pilot


- **Career**
  - IBM – CAD/CAM Numerical Control
  - McDonnell Douglas – Engineering
  - Boeing – IT
    - System Development
    - Artificial Intelligence
    - Numerical Control
    - Define eBusiness data standards (ISO 15000 ebXML, OAGIS, and OASIS UBL)
- **Current Role**
  - Enterprise Architect enabling global business
- **Hobbies**
  - Travel, Flying, Photography, Painting…

# Agenda



- **3D Printing**
- **Current Data File Format**
  - STereoLithography (STL)
- **Future Data File Format**
  - Additive Manufacturing Format (AMF)
  - 3D Manufacturing Format (3MF)
- **Impact to the value stream**

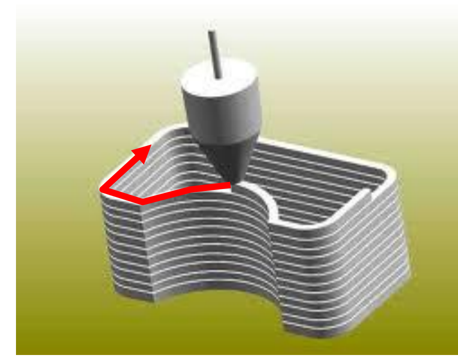
# Definitions



## What is Additive Manufacturing?

- Additive Manufacturing (AM) refers to a process by which digital 3D design data is used to build up a component in layers by depositing material. (from the International Committee F42 for Additive Manufacturing Technologies, ASTM)

- The term “3D printing” is increasingly used as a synonym for AM. However, the latter is more accurate in that it describes a professional production technique which is clearly distinguished from conventional methods of material removal.



Additive Manufacturing

Conventional Manufacturing

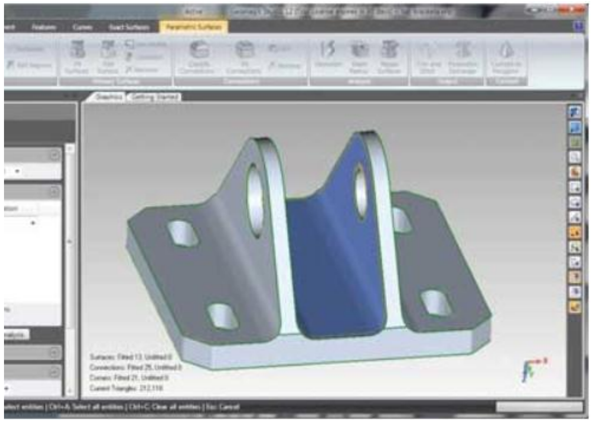
From http://www.eos.info/additive_manufacturing/for_technology_interested

ajhart@mit.edu | AM 2015-5

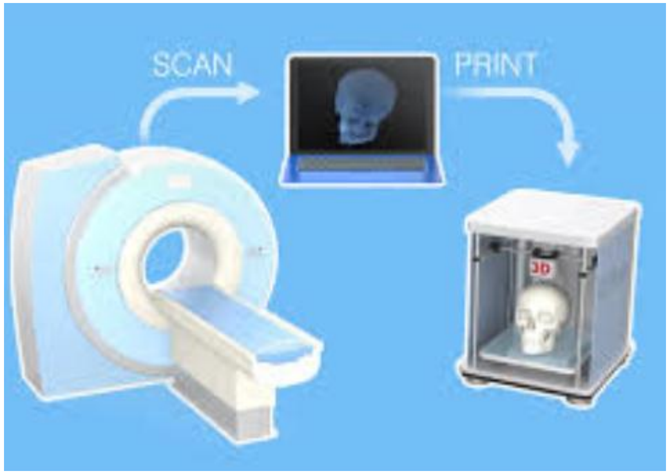
**American Society for Testing and Materials (ASTM)**

# 3D Model Creation

Global Product Data Interoperability Summit | **2015**



CAD System




CT/MRI
(Surface and internal)


3D Scanner
(Surface only)

All can generate STL file format as input to 3D Printers

# From Model to Part



## From CAD to part; appreciate the complete process.

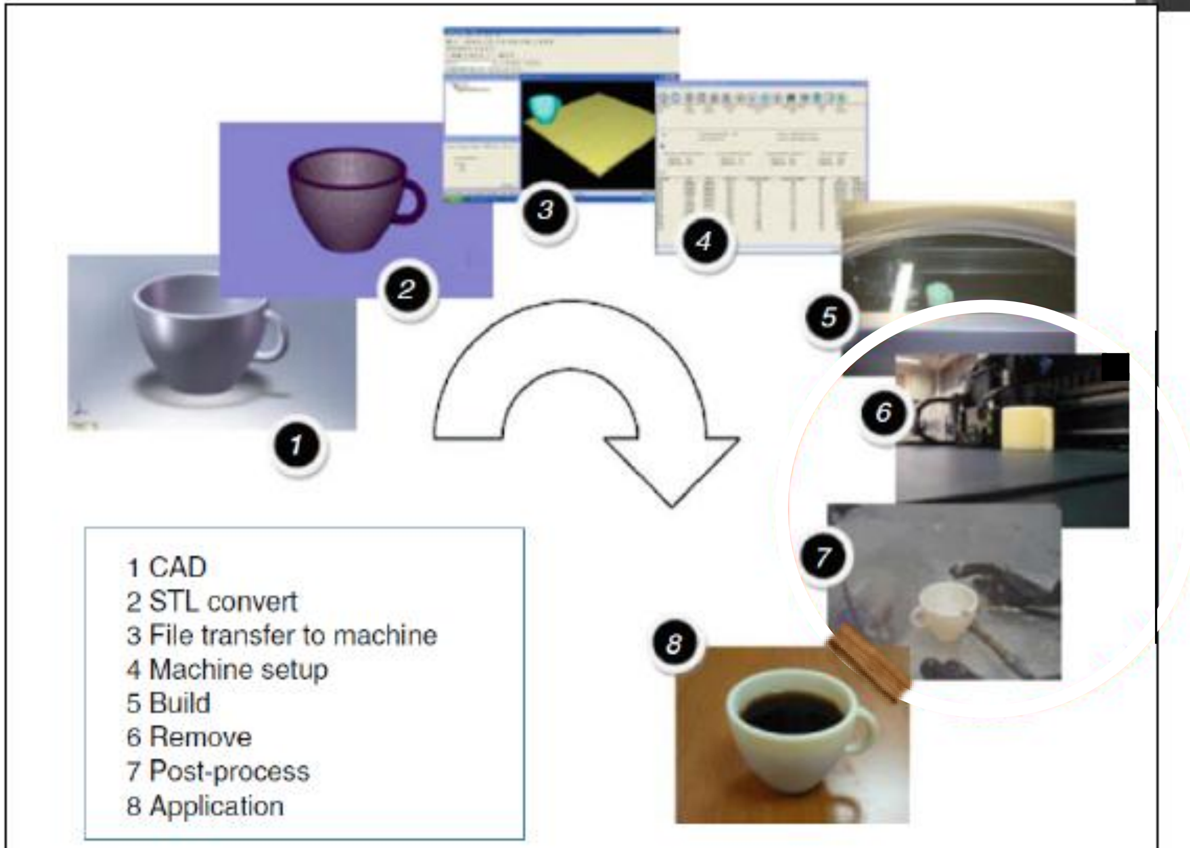



**Fig. 1.2** Generic process of CAD to part, showing all 8 stages

Gibson, Rosen, and Stucker. Additive Manufacturing Technologies

ajhart@mit.edu | AM2015 – 16

# Additive Manufacturing Process - Vat Photopolymerization

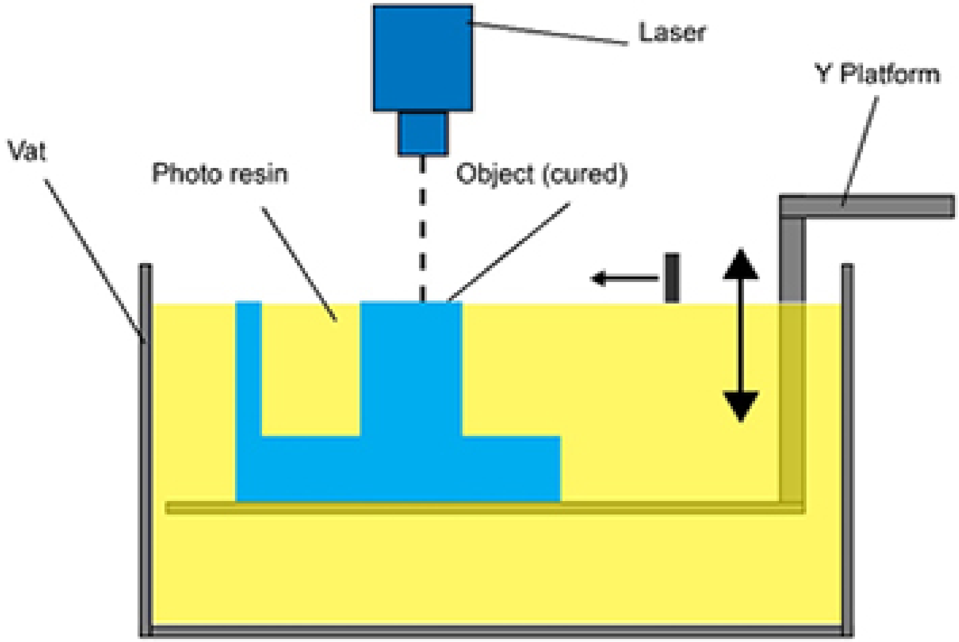


**Technology**: Stereolithography Apparatus (SLA)

**Description**: Curing a photo-reactive resin with a UV laser

**Advantages:**
- High level of accuracy and good finish
- Relatively quick process
- Typically large build areas: objet 1000: 1000 x 800 x 500 and max model weight of 200 kg

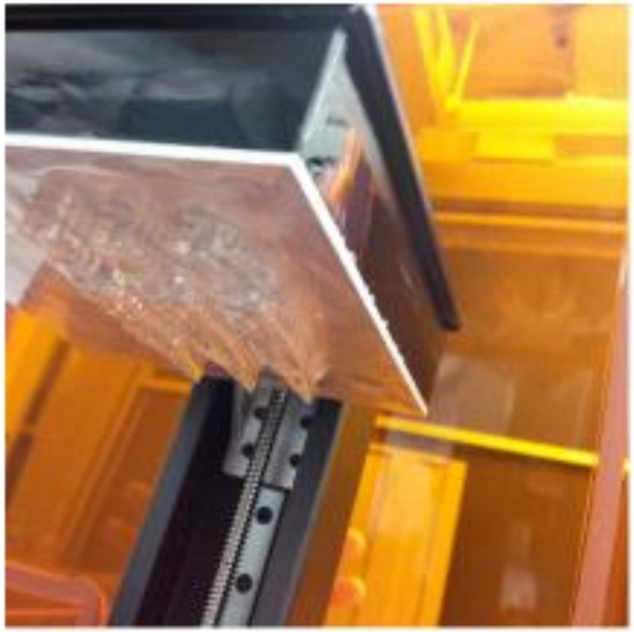
**Disadvantages:**
- Relatively expensive
- Lengthy post processing time and removal from resin
- Limited material use of photo-resins
- Often requires support structures and post curing for parts to be strong enough for structural use

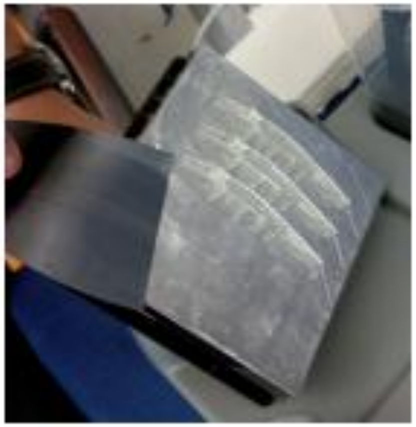



http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/

# Vat Photopolymerization - Pictures







# Additive Manufacturing Process – Material Extrusion



**Technology**: Fused Deposition Modeling (FDM)

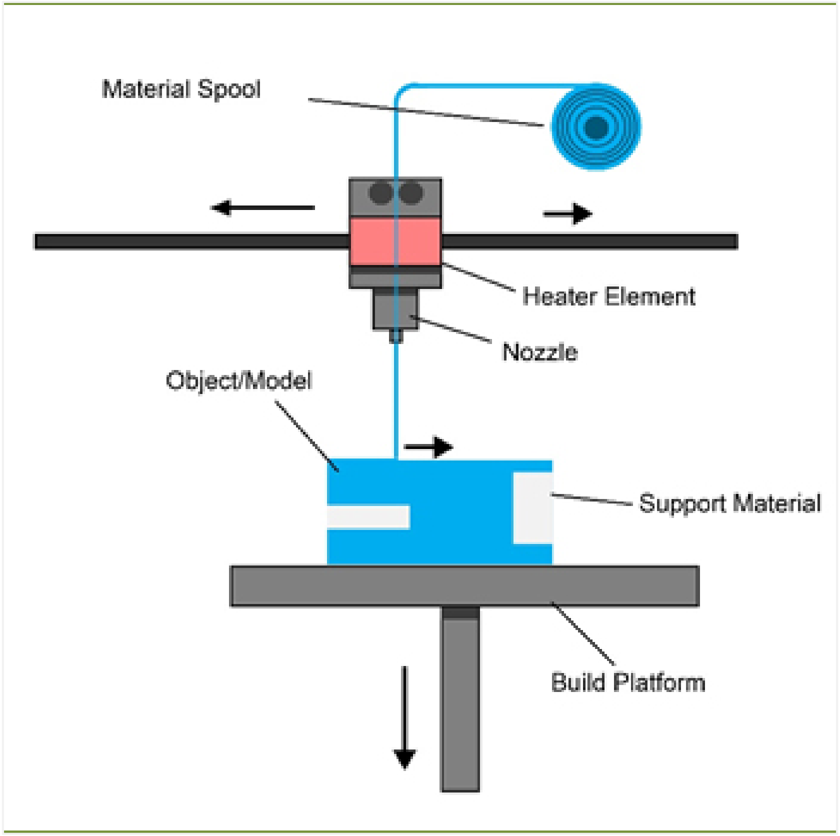
**Description**: laying down material in layers with nozzle

**Advantages:**

- Widespread and inexpensive process
- ABS plastic can be used, which has good structural properties and is easily accessible

**Disadvantages:**

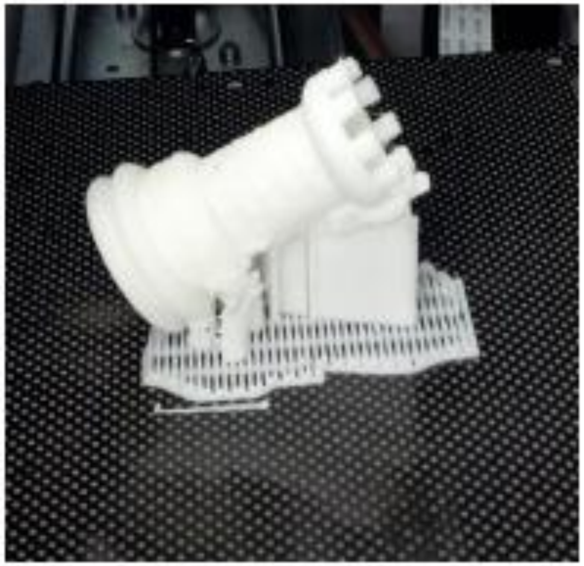
- The nozzle radius limits and reduces the final quality
- Accuracy and speed are low when compared to other processes and accuracy of the final model is limited to material nozzle thickness
- Constant pressure of material is required in order to increase quality of finish




http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/

# Material Extrusion - Pictures





# Additive Manufacturing Process – Powder Bed Fusion



**Technology**: Selective Laser Sintering/ Selective Laser Melting (SLS/SLM)

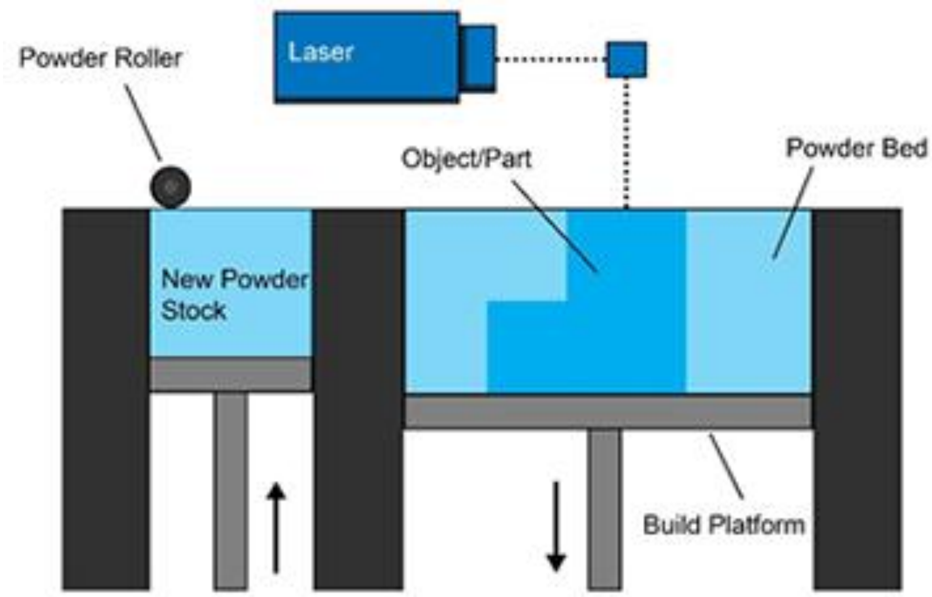
**Description**: Uses laser or electron beam to melt powdered

**Advantages:**

- Relatively inexpensive
- Suitable for visual models and prototypes
- Large range of material options

**Disadvantages:**

- Relatively slow speed
- Lack of structural properties in materials
- Size limitations
- High power usage
- Finish is dependent on powder grain size




http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/

# 7 Additive Manufacturing Processes (from ASTM F42)



- **VAT Photopolymerization** - uses ultraviolet (UV) light to cure or harden a vat of liquid photopolymer resin
- **Material Jetting** – Similar to ink jet printers, droplets of build material are deposited from the print head onto build platform, solidify and make up the part
- **Binder Jetting** - uses two materials, powder and binder, deposits alternating layers to build the part
- **Material Extrusion** – solid Material is drawn through a heated nozzle and deposited layer by layer on build platform
- **Powder Bed Fusion** - use either a laser or electron beam to melt and fuse material powder together layer by layer
- **Sheet Lamination** – bonding sheets of material together
- **Directed Energy Deposition** - similar to material extrusion, but the nozzle can move in multiple directions and using a laser or electron beam to melt the deposited build power

# Process and Material – enabler for new design

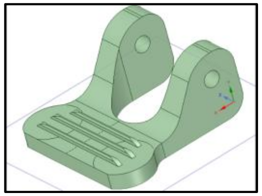


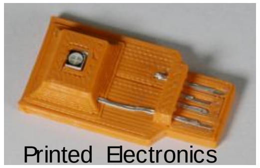
| Process | Technology | Feedstock | Metal | Ceramics | Thermoplastics | Thermosets | Biomaterials | Composites | Multi-Material | Others |
|---|---|---|---|---|---|---|---|---|---|---|
| **Extrusion** | FDM | Solid | | ● | ● | | ● | ● | Yes | Wood, Food |
| **Material Jetting** | MJ | Liquid | | | ● | ● | | | Yes | |
| | PJ | Liquid | | | ● | ● | | | Yes | |
| **Binder Jetting** | 3DP | Powder | ● | ● | | | | | No | Sugar, Plaster |
| **Sheet Lamination** | LOM | Solid | ● | | | | | | Yes | Paper |
| **VAT Photopolymerization** | SLA | Liquid | | | | ● | ● | ● | No | |
| | DLP | Liquid | | | | ● | ● | ● | No | |
| **Powder Bed Fusion** | SLS | Powder | ● | ● | ● | | ● | ● | No | Sugar |
| | SLM | Powder | ● | | | | ● | | No | |
| | EBM | Powder | ● | | | | ● | | No | |
| | SHS | Powder | | | ● | | | | No | |
| | HSS | Powder | | | ● | | | | No | |
| **Direct Energy Deposition** | DMP | Powder | ● | ● | | | | | No | |
| | LEMS | Powder | ● | | | | ● | ● | Yes | |

D'Angelo and Hart, In review 2015 ajhart@mit.edu |AM2015

# 3D Printed Part Classification (Todorov et al.)





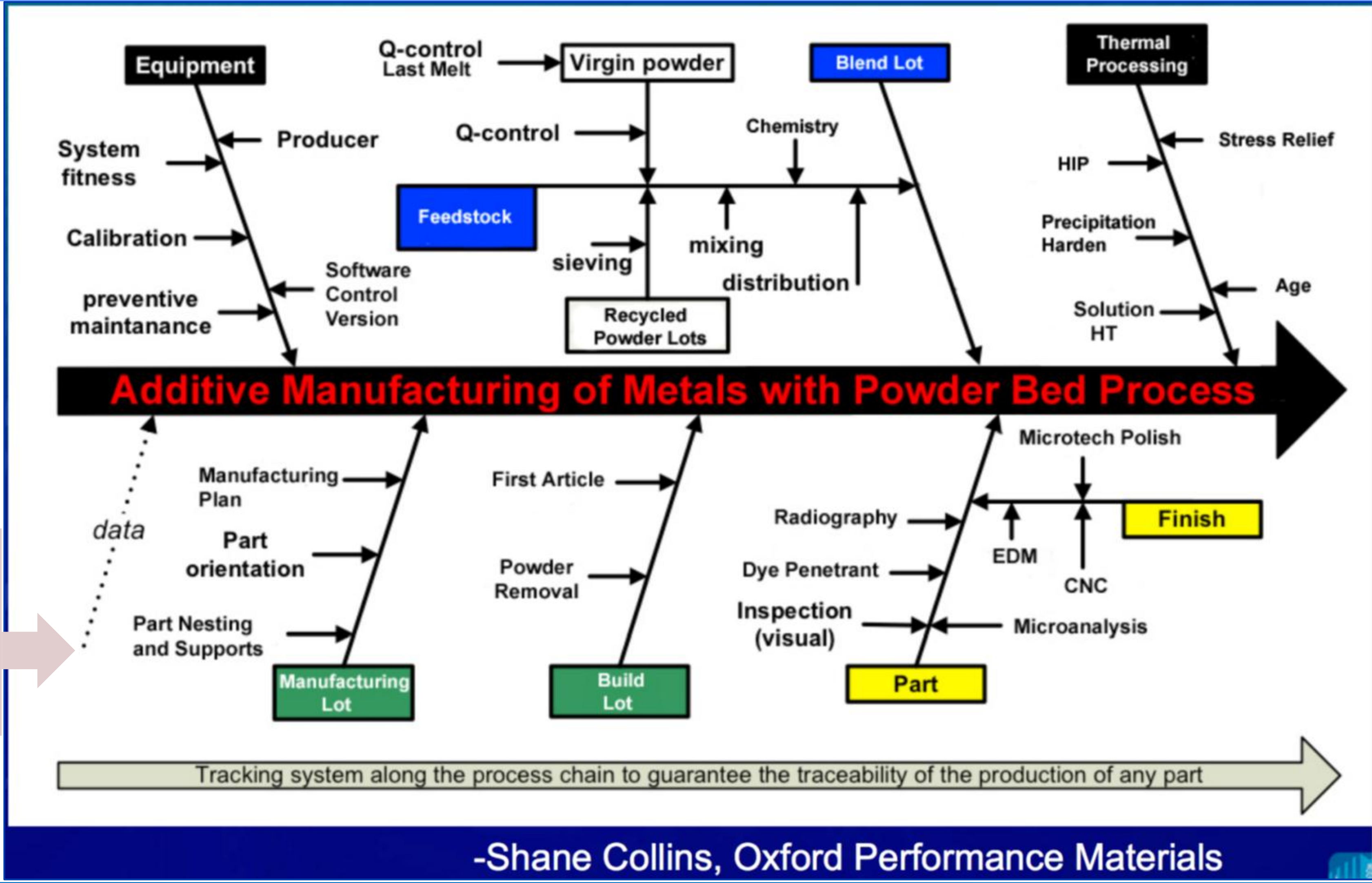



## 5 Classes

- **Simple tools and components** (i.e. those that can be made subtractively thus inspected the same way)
- **Optimized standard parts** could be made subtractively but using specialized/intricate operations.
- **Parts with embedded features** (i.e. those that requires assembly)
- **'Design for AM'** – essentially impossible by subtractive methods.
- **Lattice structures** – impossible without AM. Also most challenging to inspect.

# Factors Affecting Consistent AM Part Production

Global Product Data Interoperability Summit | **2015**




STL Model Data, Slicing Data, and G-code (tool path data)

# The Genesis of Stereolithography (STL)




**Hull's designed the STL (STereoLithography) file format widely accepted by 3D printing software as well as the digital slicing and infill strategies common to many processes today. It has lasted for the last 30 years.**

# Current Data Format Strength and Weakness



| Data Format | Strength | Weakness |
|---|---|---|
| Stereolithography (STL) | Simple, portable, does not require large amount of RAM process, describe surface geometry of a 3D object | Geometry accuracy, does not represent color, texture, material, and orientation. Does not scale well for high resolution and lattice. Duplicate information and inconsistence. |
| X3D Virtual Reality Modeling Language (VRML) | allow 3D content to be viewed over the web, includes information about a 3D surface and its color | contains information not relevant for AM, such as transparency, animations, lights, sounds, and embedded navigation URLs. Cannot define multiple materials within a given mesh or arbitrary microstructure. |
| STEP | defines the geometric shape of a product: includes topology, features, tolerance, material properties, etc. necessary to completely define a product for the purposes of design, analysis, manufacture, test, inspection and product support. | unnecessarily complex for the needs of AM |
| IGES | IGES was originally developed for the exchange of drafting data like 2D/3D wireframe | not design for AM with high barrier to entry |
| PLY | models, text, dimensioning data, and a limited class of surfaces. | does not define materials or microstructure volumetrically |
| SAT | widely used for boundary-representation (B-Rep) objects in CAD packages | format revolves around its internal topological data structure, which makes it difficult to understand and unsuitable for an exchange format |
| OBJ | simple, compact, widely accepted in the 3D modeling community, and can map textures easily | lacks the ability to define materials or microstructure volumetrically |
| DXF | design for exchange 2D/3D wireframe data, allows the definition of 3D triangle meshes and solids best suited for 2D drawings | not for 3D objects |
| 3DS | Can include color and texture information. It is limited to 65536 vertices and polygons | contains much information not necessary for the AM industry, such as lighting and animation info |
| SLC | format represents individual 2D slices of a 3D object as contours representing internal and external boundaries | not suitable for a cross-platform interchange format |

# Characteristics of Good Data File Format



- **<u>Technology independence</u>**
  - Describes the object, not how to make it
  - Any machine can make the part to the best of its ability
- **<u>Simplicity</u> -** easy to implement and understand
- **<u>Scalability</u> –** can handle complex objects, microstructures, etc.
- **<u>Performance</u> –** reasonable read/write time, file size, processing, and accuracy
- **<u>Backwards compatibility</u> -** can convert to/from original format without additional information
- **<u>Future compatibility</u> –** ability to include new features easily

# Future Data File Formats



- Additive Manufacturing Format (AMF)
- 3D Manufacturing Format (3MF)

# Additive Manufacturing File Format (AMF) - ISO Standard



**ISO/ASTM 52915:2013** **Describes a framework for an interchange format to address the current and future needs of additive manufacturing technology…**

**Current Version: 1.2**

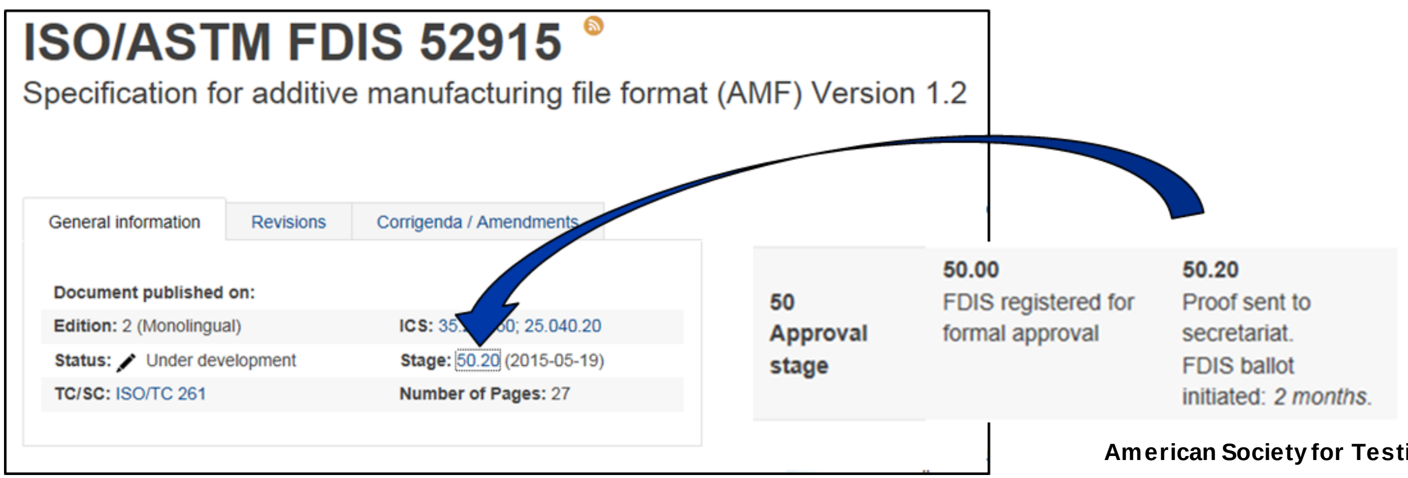
**Released By: [ISO / ASTM52915]**

**Developed by Subcommittee: [F42.04]**

**Initial Release: May 2011**

**Extension: .amf  File Type: XML format**

**Advantages of using a W3C XML : Human readable, Technology independent, Extensible, text based, and compressible.**




**American Society for Testing and Materials (ASTM)**

# AMF General Concept



## *Sample*

```
<?xml version="1.0" encoding="UTF-8"?>
<amf units="mm">
  <object id="0">
    <mesh>
      <vertices>
        <vertex>
          <coordinates>
            <x>0</x>
            <y>1.32</y>
            <z>3.715</z>
          </coordinates>
        </vertex>
        <vertex>
          <coordinates>
            <x>0</x>
            <y>1.269</y>
            <z>2.45354</z>
          </coordinates>
        </vertex>
        ...
      </vertices>
      <volume>
        <triangle>
          <v1>0</v1>
          <v2>1</v2>
          <v3>3</v3>
        </triangle>
        <triangle>
          <v1>1</v1>
          <v2>0</v2>
          <v3>4</v3>
        </triangle>
        ...
      </volume>
    </mesh>
  </object>
</amf>
```

http://amf.wikispaces.com/file/view/amf.xsd/402895728/amf.xsd

**<Object>** is the root element in the AMF

- **Objects** (parts) defined by volumes and materials
  - Volumes defined by triangular mesh
  - Materials defined by properties/names
- **Color, Texture**
- **Materials** can be combined
  - Graded materials
  - Lattice / Mesostructure orientation
- **Print Constellations** - printing groups of same or different objects
- **Increased Geometric Accuracy**
  - Addresses vertex duplication and leaks of STL
  - Add normal/tangent vectors to triangle mesh edges to produce accurate geometry
- **Future** : Tolerances, data encryption, copy right, external references, subassemblies, process control, etc.

ELYSIUM Parker NORTHROP GRUMMAN BOEING GLOBAL PRODUCT DATA INTEROPERABILITY SUMMIT 2015

# 3D Manufacturing Format (3MF) Industry Consortium

**launched on April 30, 2015**



***"With the rapid adoption of 3D printing capabilities and increased usage across industries, the need for a file format that can accurately and completely transfer data from a CAD system to a 3D printer became instantly obvious," stated Gian Paolo Bassi, CEO, SOLIDWORKS, Dassault Systèmes.***

Founding Members of the 3MF Consortium are:

AUTODESK. DASSAULT SYSTEMES hp Microsoft

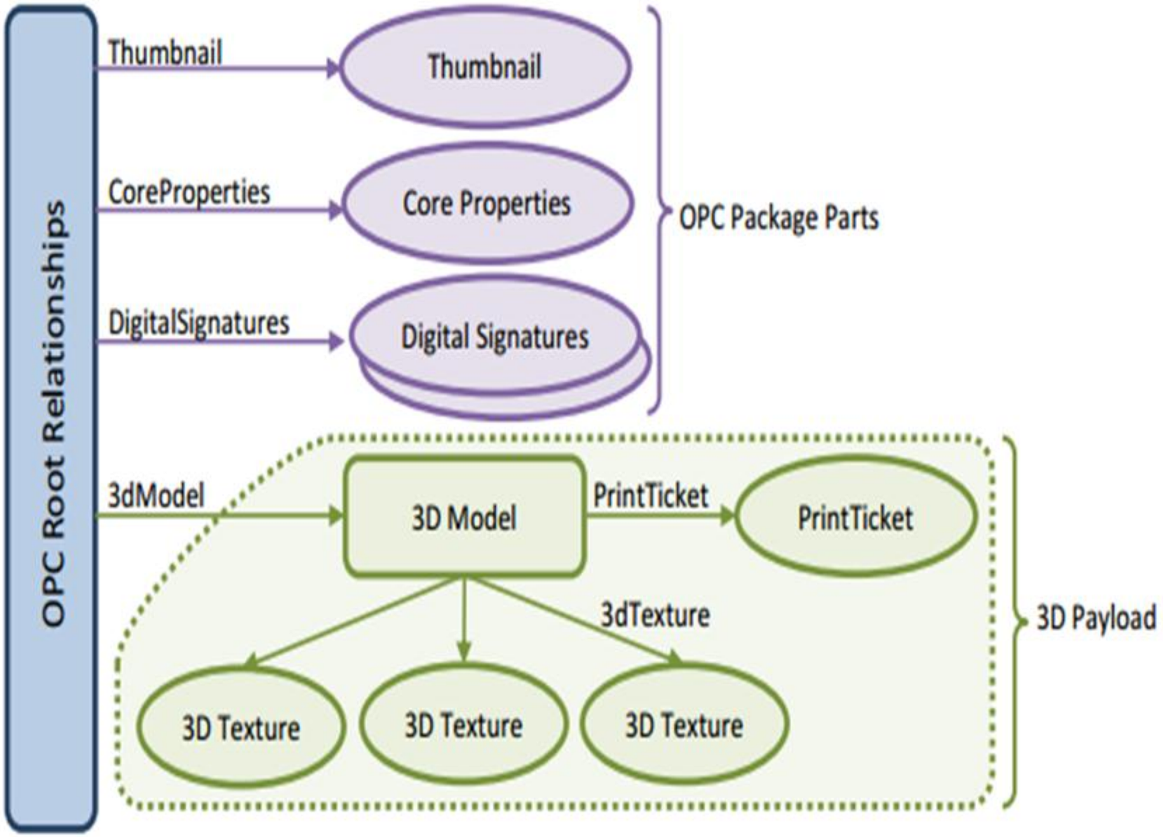
netFabb shapeways SLM SOLUTIONS

http://3dprintingindustry.com/2015/04/30/microsoft-announces-3mf-consortium-for-3d-printing-file-format/

# 3MF



**3MF is an industry consortium working to define a 3D printing format that will allow design applications to send full-fidelity 3D models to a mix of other applications, platforms, services and printers**




http://www.3mf.io/

# 3MF Schema



<model> is the root element of the 3MF document

<model>
:
:
:
:
</model>

**An XML Schema describes the data structure of an XML document**

*3D Manufacturing Format Specification and Reference Guide*

```
    <xs:restriction base="xs:string">
      <xs:enumeration value="model"/>
      <xs:enumeration value="support"/>
      <xs:enumeration value="other"/>
    </xs:restriction>
  </xs:simpleType>
  <!-- Elements -->
  <xs:element name="model" type="CT_Model"/>
  <xs:element name="resources" type="CT_Resources"/>
  <xs:element name="build" type="CT_Build"/>
  <xs:element name="basematerials" type="CT_BaseMaterials"/>
  <xs:element name="base" type="CT_Base"/>
  <xs:element name="object" type="CT_Object"/>
  <xs:element name="mesh" type="CT_Mesh"/>
  <xs:element name="vertices" type="CT_Vertices"/>
  <xs:element name="vertex" type="CT_Vertex"/>
  <xs:element name="triangles" type="CT_Triangles"/>
  <xs:element name="triangle" type="CT_Triangle"/>
  <xs:element name="components" type="CT_Components"/>
  <xs:element name="component" type="CT_Component"/>
  <xs:element name="metadata" type="CT_Metadata"/>
  <xs:element name="item" type="CT_Item"/>
</xs:schema>
```

*3MF Materials and Properties Extension Specification and Reference Guide*

```
    </xs:restriction>
  </xs:simpleType>
  <xs:simpleType name="ST_ResourceIndex">
    <xs:restriction base="xs:nonNegativeInteger">
      <xs:maxExclusive value="2147483648"/>
    </xs:restriction>
  </xs:simpleType>
  <!-- Elements -->
  <xs:element name="texture2d" type="CT_Texture2D"/>
  <xs:element name="colorgroup" type="CT_ColorGroup"/>
  <xs:element name="color" type="CT_Color"/>
  <xs:element name="texture2dgroup" type="CT_Texture2DGroup"/>
  <xs:element name="tex2coord" type="CT_Tex2Coord"/>
  <xs:element name="compositematerials" type="CT_CompositeMaterials"/>
  <xs:element name="composite" type="CT_Composite"/>
  <xs:element name="multiproperties" type="CT_MultiProperties"/>
  <xs:element name="multi" type="CT_Multi"/>
</xs:schema>
```

# AMF and 3MF - Print Difference



| AMF | 3MF |
|---|---|
| .AMF + Slicer + G-code<br><br>1. Create Model and Save file<br>2. Setup the Slicer with required settings, Slice it (and save/copy the G-code)<br>3. Use that G-code to print the object | .3MF<br><br>1. Create Model and Save file<br>2. Click Print and select the 3D printer and required settings, hit OK |

# New AM Design



3D printed T25 sensor enclosure unit produced by GE Aviation and certified by FAA. Image credit: GE Aviation

GE is currently partnering with Boeing to install this new part in over 400 of its GE90-94B engines used on the new high-tech Boeing 777 aircraft.

3d printed fuel nozzle.

This 3d printed part is five times as durable as regularly produced one, 25% lighter, runs cooler because of internal cooling structures, only one part instead of 18.

## Boeing files patent for 3D-printed aircraft parts

March 16, 2015

Besides Boeing trying to patent the 3d printing of aircraft parts it is also trying to patent the entire system around it including: “a parts library, a database, a parts management system, and a three dimensional printing system.” Boeing describes a method and apparatus for requesting, authorizing, printing, and even paying for aircraft parts under the simple title: “Three Dimensional Printing of Parts”. Simple title, HUGE impact and implications!

http://www.geekwire.com/2015/boeing-files-patent-for-3d-printing-of-aircraft-parts-and-yes-its-already-using-them/

# Future of Manufacturing is Here



Cars built for local market needs - enabled by AM and co-creation platforms

Product will be co-designed using SMAC (Social, Mobile, Analytic, Cloud) and enabled by 3D printer





**What is a Microfactory?**

The Microfactory brings the worldwide Local Motors community together and allows for the creation and production of new vehicles based on local needs. Leveraging the Co-Creation platform produces innovative designs from community members in over 130 countries. The Microfactory brings those designs to life.

Sources: Local Motors

# Summary



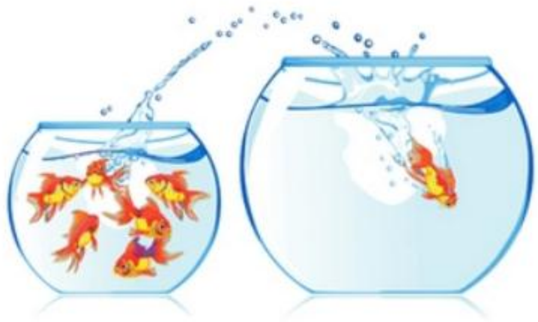
Presented the three most common 3D printing technologies and processes

Discussed the current STL data format limitations

Listed the characteristics of good data format

Reviewed the two future Additive Manufacturing data formats, AMF and 3MF, and understand the key differences.

*3D Printing technology with the new data format enables innovative ideas through out the value chain from design, to manufacturing, to supply chain, to new business opportunities*



# Q & A



**Thank you!**

**Sally.m.chan@Boeing.com**