Additive Manufacturing: Standards & Other International Trends

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Chairman, ASTM F42 Committee on Additive Mfg. Tech.

DARPA Information Science & Technology board member

University of Louisville's Involvement in AM

- One of the best equipped additive manufacturing (AM) facilities in the world
- Performing federally-funded basic and applied research, technology transfer, and industry-funded projects ***in AM since starting with SLS in 1993***
- Over 20 people focused on AM
- Partner of leading AM users
  - Boeing, GE, DoD, Integra, service bureaus, etc.
- Over 70 member organizations in our RP Center
  - Includes Haas Technical Education Center

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AM Equipment at UL

- Polymer Laser Sintering (LS)
  - 3D Systems (DTM) 2500 plus (with Multi-zone heating)
  - 3D Systems (DTM) 2500CI High Temperature Research Platform
    - Multi-zone heating
    - High Speed Scanning
- Direct Metal Laser Sintering (DMLS)
  - EOS M270 Dual Mode
- Electron Beam Melting (EBM)
  - Arcam S400
- ExOne 3D Printing
  - Dental machine
- Ultrasonic Consolidation (UC)
  - Fabrisonic R200 High Power
  - Solidica Formation Beta Machine
- Laser Engineered Net Shaping
  - Optomec LENS 850
- Fused Deposition Modeling
  - Stratasys uPrint
  - Several desktop, educational “material extrusion” machines
- Stereolithography
  - 3D Systems SLA 250/30
- Direct Write
  - nScrypt Direct Write head

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Some of the On-Going AM Research at UofL

- Navy-funded work
  - Modeling and control of Ultrasonic Consolidation
  - Comprehensive materials testing of metals and polymers made using UC, SLS, DMLS, EBM & FDM
  - Development of a material for accurate magnetic scale models
- Air Force-funded work
  - Modeling of metal laser sintering of Ti 6/4
  - Thermal understanding and control in polymer laser sintering
- NSF-funded work
  - Modeling of Friction Surfacing of Inconel superalloys and Stainless Steels
- NIST-funded work
  - Modeling of metal laser sintering of Inconel 625
- Industry-funded work
  - Monitoring & layer-by-layer validation of parts made using DMLS

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History of ASTM F42 Committee

- SME RTAM initiated planning May 2008
- Contact made with ASTM Int’l July 2008
- ….planning/organizational meetings
- 1st F42 Meeting May 27-28, 2009 – Philadelphia
- ….meetings alternate between USA & Europe
- 8th Meeting January 15-16, 2013 – Atlanta, GA
- 9th Meeting July 2012 (with ISO TC261) Nottingham, UK

Additive Manufacturing

Current Organizational Structure

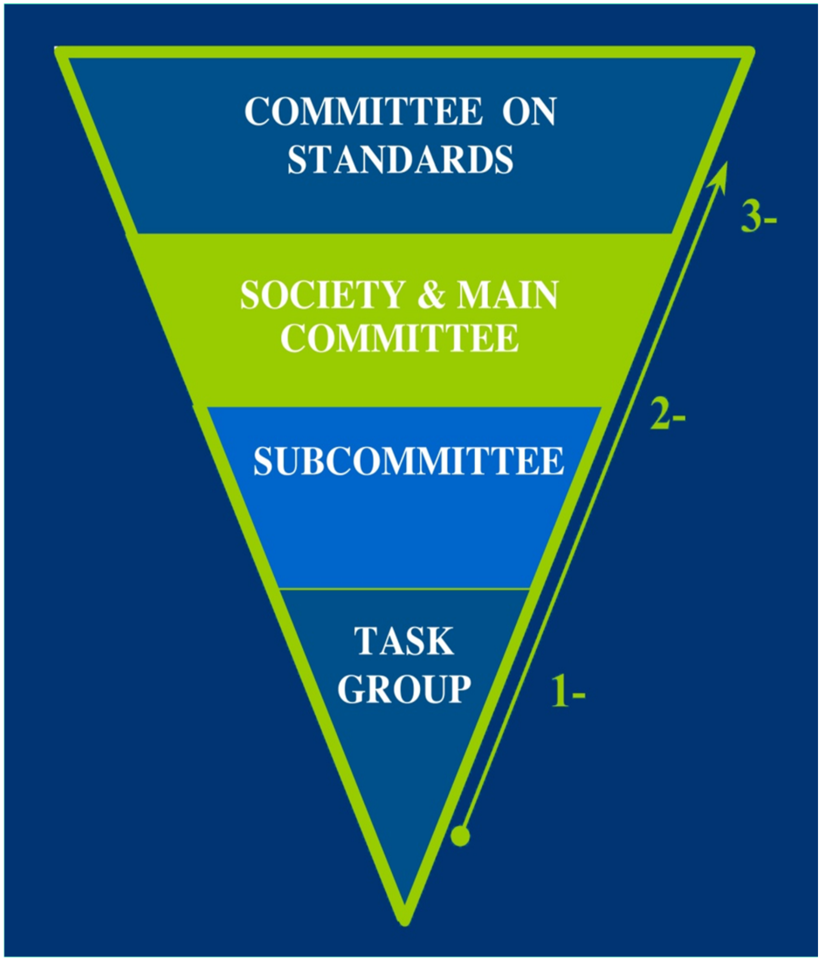
- Main Committee Officers
  - Brent Stucker (University of Louisville), Chairman
  - Carl Dekker (Met-l-flo), Vice-Chairman
  - Chris Tuck (Loughborough University), Recording Secretary
  - Connie Phillips (NCMS), Membership Secretary
- Five Subcommittees
  - Test Methods (Jason Davidson, Chair)
  - Materials and Processes (Shane Collins, Chair)
  - Design (Evan Malone, Chair)
  - Terminology (Terry Wohlers, Chair)
  - U.S. TAG for ISO 261 (Mary Kinsella, Chair)

Committee Scope

- The promotion of ***knowledge***, stimulation of ***research*** and ***implementation of technology*** through the development of standards for additive manufacturing technologies.
- The work of this Committee will be coordinated with other ASTM technical committees and other national and international organizations having mutual or related interests.

How standards are developed

- Drafted by Task Groups
- Balloted by Subcommittee
- Balloted by Main Committee
- Approved by ASTM



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Key Accomplishments to Date

- Terminology
  - Including Process Category Names
- AMF File Format
- Testing Terminology
- Ti 6/4 Powder Bed Processing

Additive Manufacturing

General Observations of process

- *Task Group Chair initiative is the key to success*
- Create relatively complete draft standards quickly in small groups or as individuals
  - Circulate to Task Group (with deadline)
  - **Circulate to Subcommittee (with deadline)**
  - Ballot the proposed standard as soon as it is ready – regardless of when that falls w.r.t. meetings
    - Ballot at subcommittee
    - Ballot at Main committee
      - sometime in parallel to subcommittee if it was revised based on input

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Current State in ASTM F42

- Since 2009, F42 standards have been pursued using a bottom-up, needs-based approach
  - Self-organizing groups with common interests and needs working together to address their highest priority
- This was the correct approach for a new start-up standards organization
  - Got many people involved right away on subjects that they were passionate about (momentum, excitement)
  - Jump-started lots of industry engagement and quick progress on needed AM standards

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International Standards Accomplishments this Year

- Terminology
  - **Process Categories!**
- Design
  - Updated AMF File Format
- Testing
  - Coordinate Systems & Part Location/Orientation
- Materials & Processes
  - Ti 6/4 Powder Bed Processing
- ISO TC 261
  - Signed agreement
  - Beginning adoption of ASTM standards

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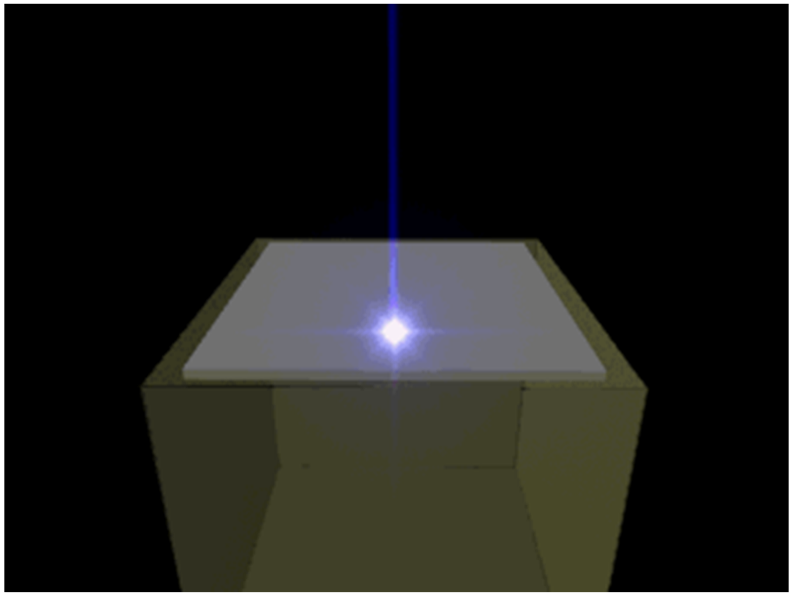
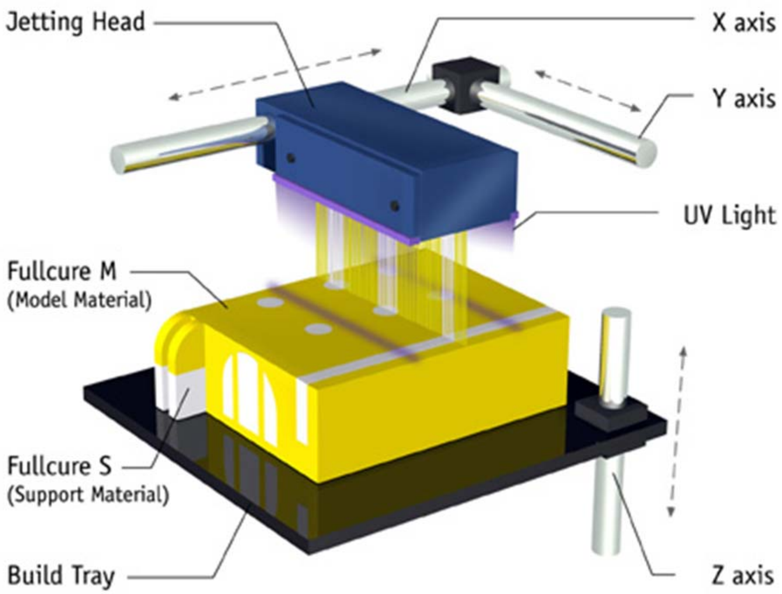
Vat Photopolymerization Process

- An additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization. (Reprinted, with permission from ASTM F2792-08. Copyright ASTM International.)
  - Stereolithography
  - Envisiontec DLP
  - Micro-SLA
  - …



Material Jetting

- An additive manufacturing process in which droplets of build material are selectively deposited. (Reprinted, with permission from ASTM F2792-08. Copyright ASTM International.)
  - Wax or Photopolymers
  - Multiple nozzles
  - Single nozzles
  - Includes
    - Objet
    - 3D Systems Projet
    - Stratasys Solidscape machines
    - Several Direct Write machines
    - Etc…



The Objet PolyJet Process

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Binder Jetting

- An additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials.
(Reprinted, with permission from ASTM F2792-08. Copyright ASTM International.)
  - Zcorp
  - Voxeljet
  - ProMetal/ExOne
  - …

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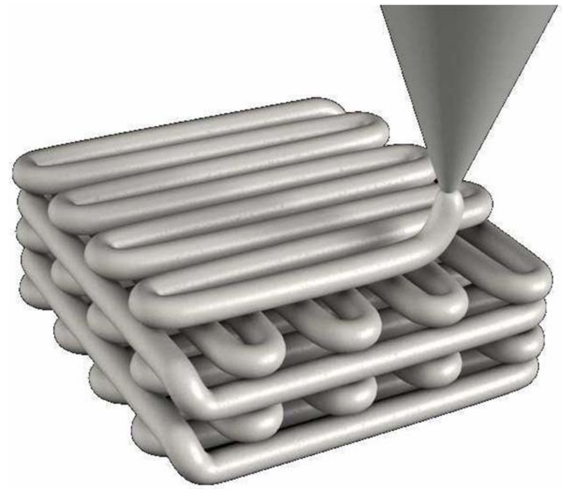
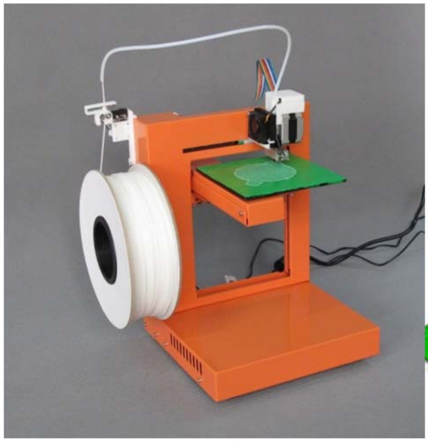
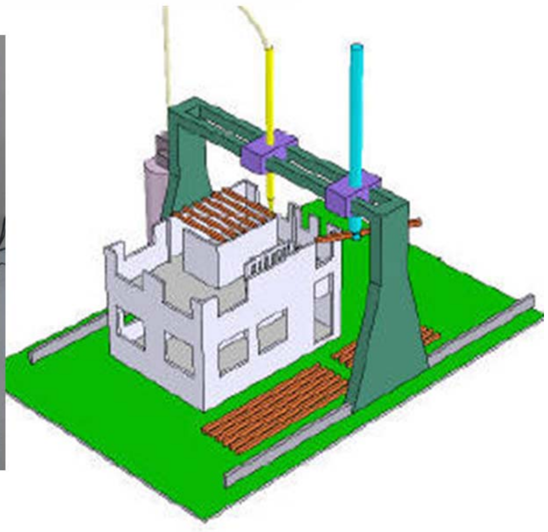
Material Extrusion



- An additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.
  (Reprinted, with permission from ASTM F2792-08. Copyright ASTM International.)
  - Based on Stratasys FDM machines
  - Office friendly
  - DIY community
  - Best selling platform
  - …





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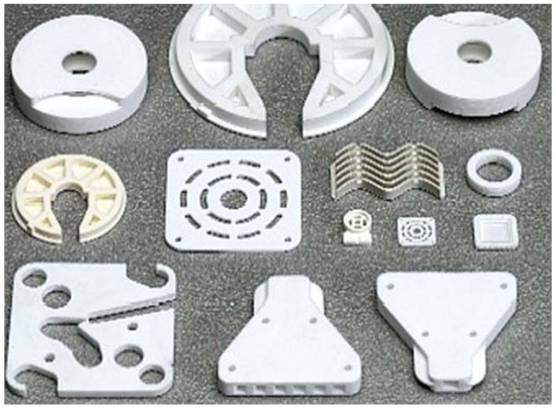
Powder Bed Fusion

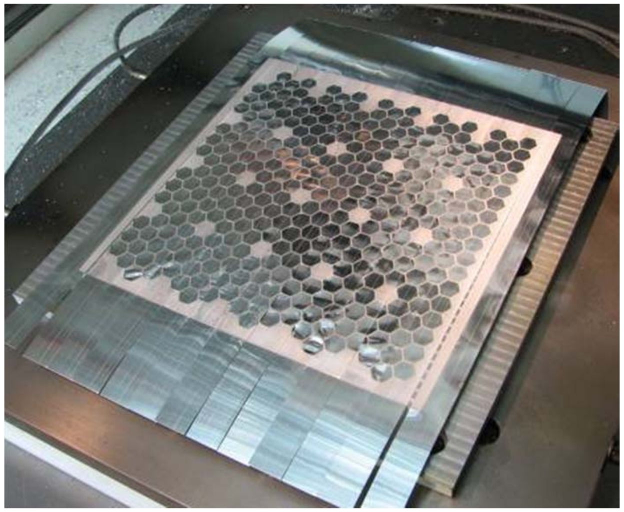
- An additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.

  - SLS, SLM, DMLS, EBM, BluePrinter, etc.
  - Polymers, metals & ceramics

Sheet Lamination

- An additive manufacturing process in which sheets of material are bonded to form an object. (Reprinted, with permission from ASTM F2792-08. Copyright ASTM International.)
  - Paper (LOM)
    - Using glue
  - Plastic
    - Using glue or heat
  - Metal
    - Using welding or bolts
    - Ultrasonic AM…





Directed Energy Deposition

- An additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited.

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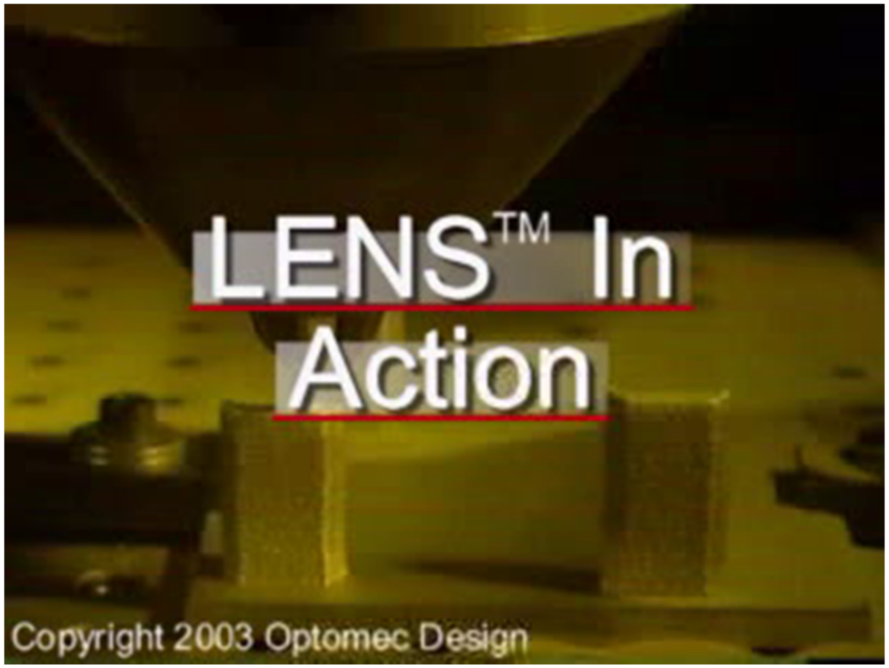

  - Wire & Powder Materials
  - Lasers & Electron Beams
  - Great for feature addition & repair

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AMF File format

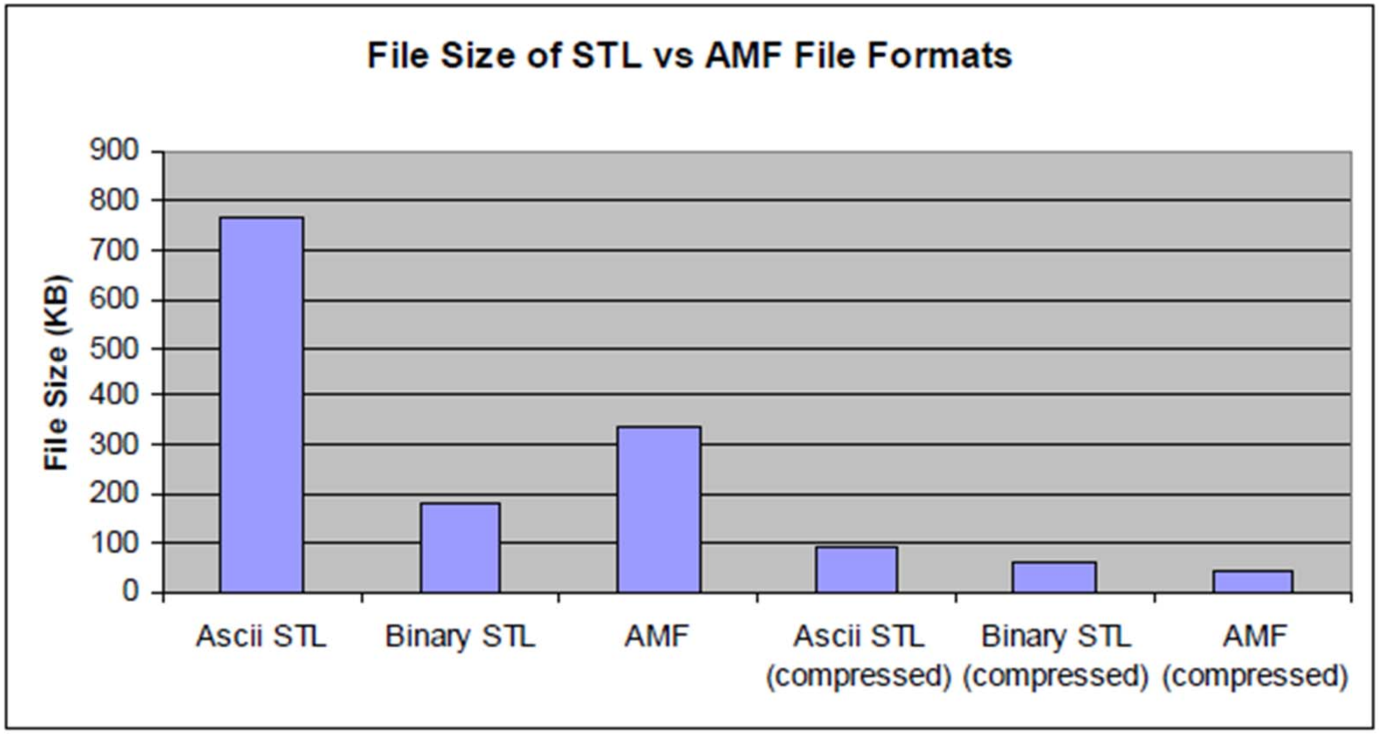
- .AMF
  - Additive Manufacturing Format
  - Additive Manufacturing File
- Open source license-free implementation
  - amf.wikispaces.com
- Next step is to work with software providers (like Microsoft & Materialise) to refine and implement the standard

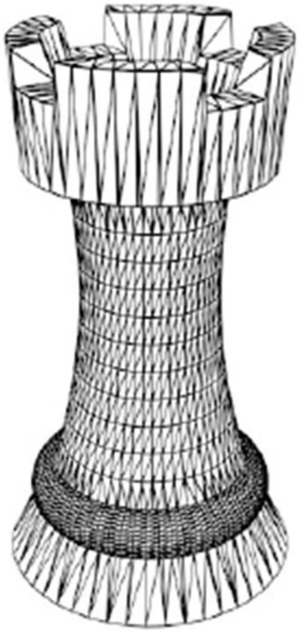
Basic AMF Structure

```
<?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>
      <region>
        <triangle>
          <v1>0</v1>
          <v2>1</v2>
          <v3>3</v3>
        </triangle>
        <triangle>
          <v1>1</v1>
          <v2>0</v2>
          <v3>4</v3>
        </triangle>
        ...
      </region>
    </mesh>
  </object>
</amf>
```

Addresses vertex duplication and leaks of STL & Units!

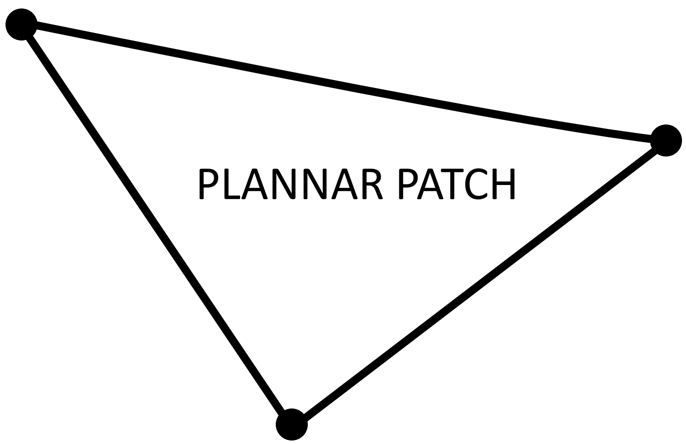
Compressibility



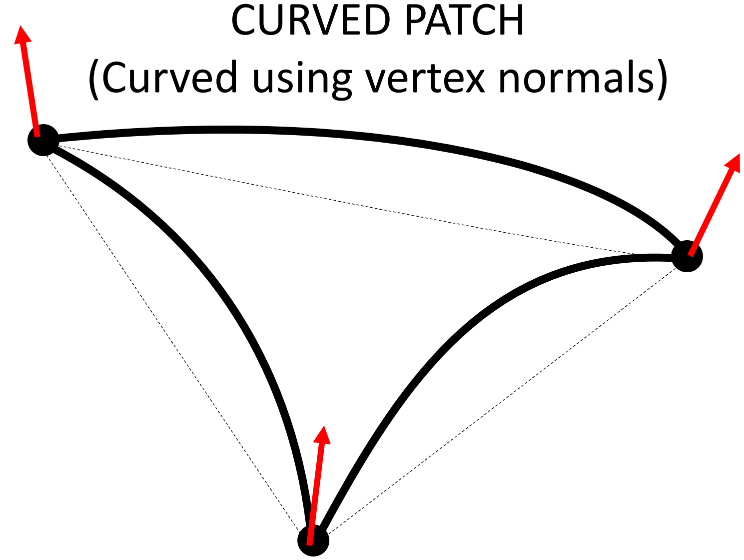


Comparison for 32-bit Floats; need to look at double precision

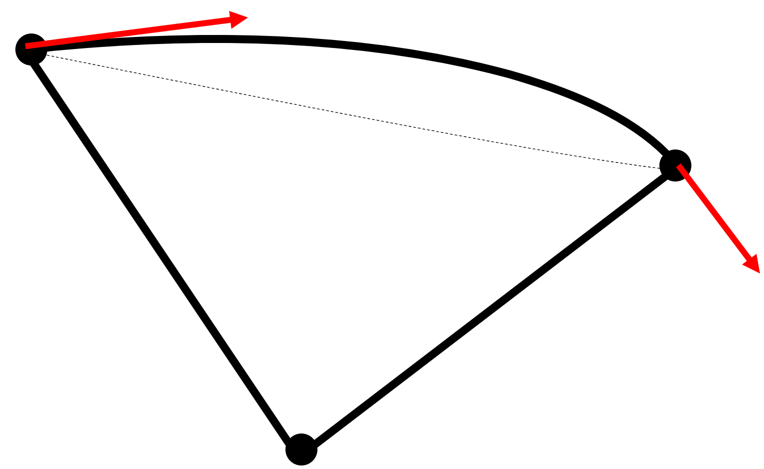
Curved patches



CURVED PATCH
(Curved using vertex normals)



CURVED PATCH
(or curved using edge tangents)

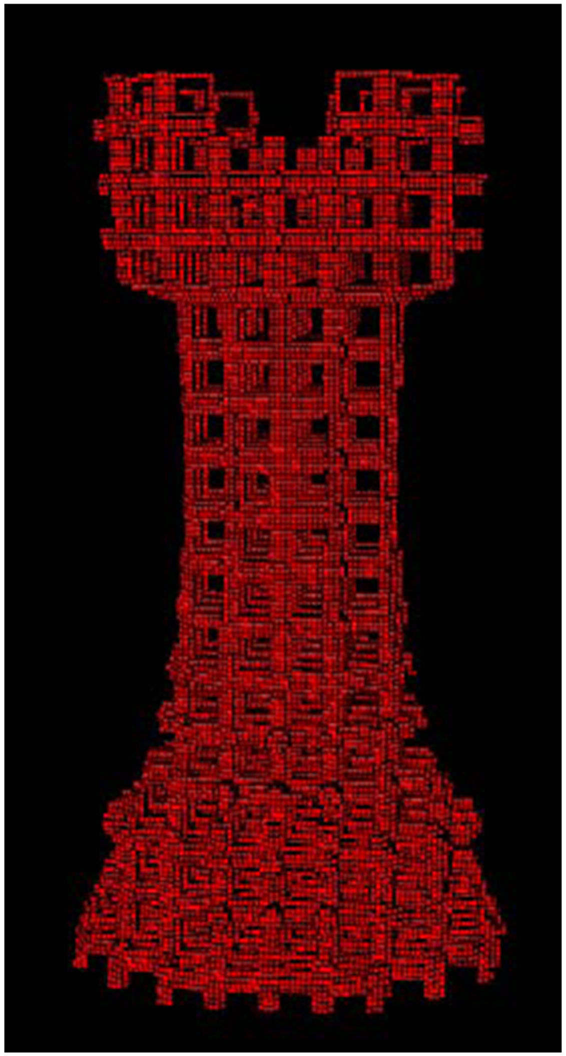


Optionally add normal/tangent vectors to some triangle mesh edges to allow for more accurate geometry.

Gradient Materials

Multiple Materials

Micro-structure



Color and Graphics

- Can be assigned to
  - A material
  - A region
  - A vertex
- Specified
  - Fixed RGBA values
  - By formula
  - By reference to an image

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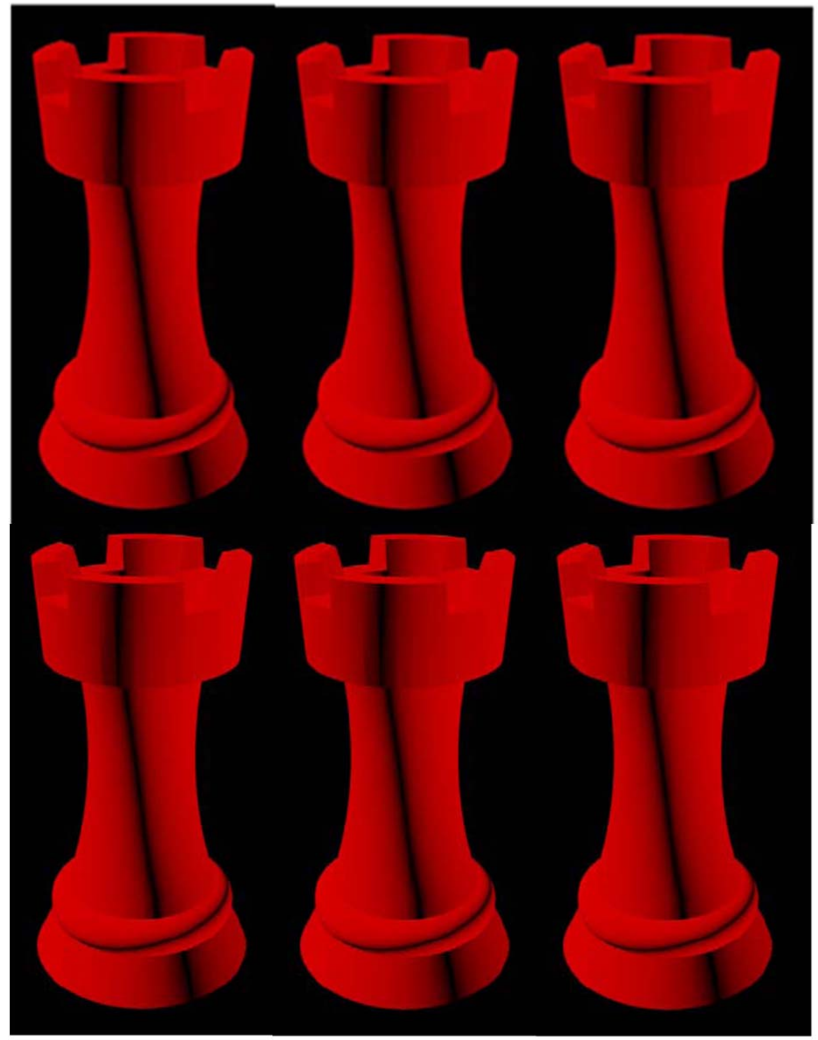
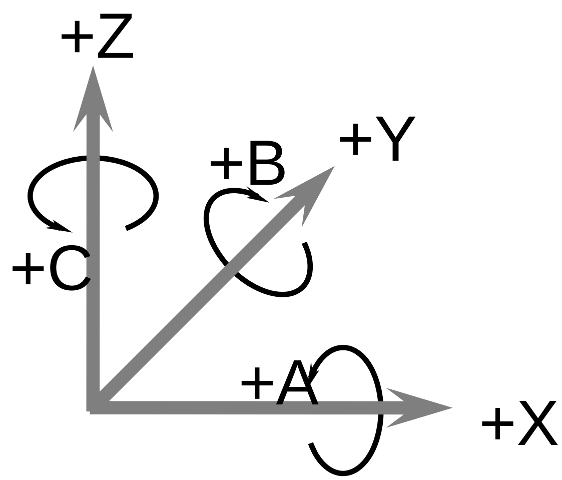
Print Constellation

- Print orientation
- Duplicated objects
- Sets of different objects
- Efficient packing
- Hierarchical

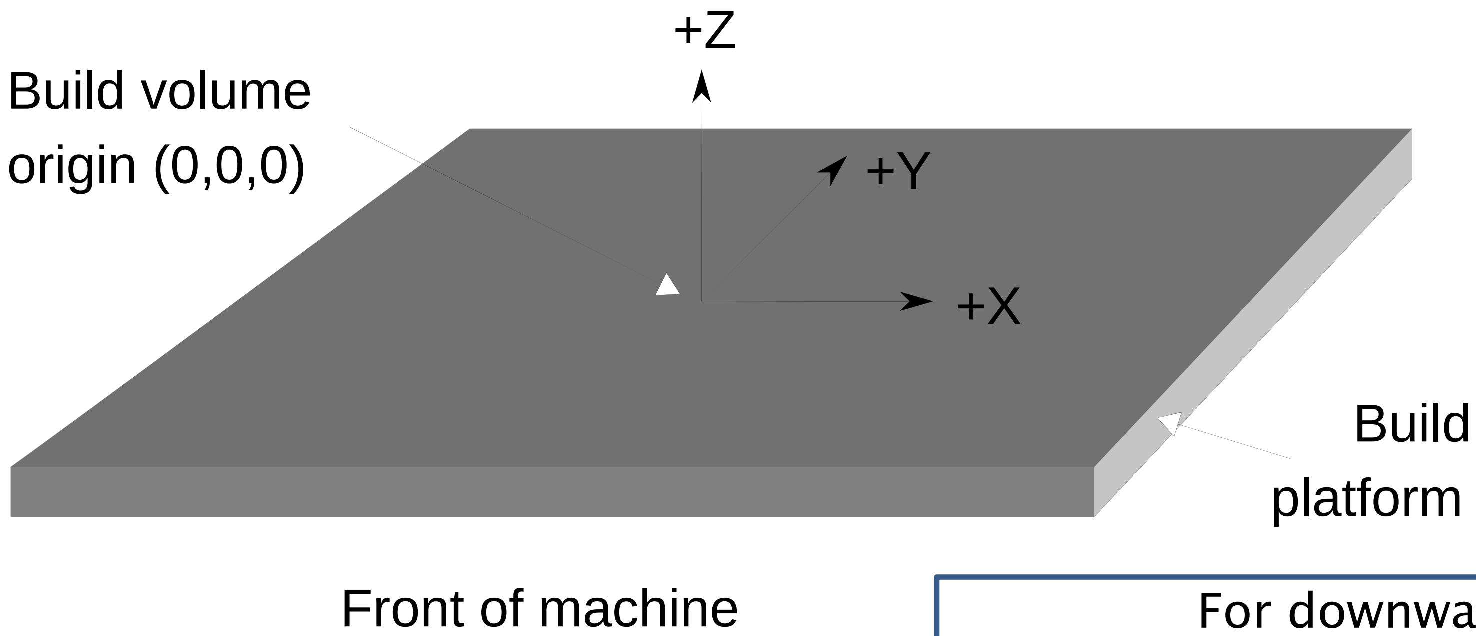


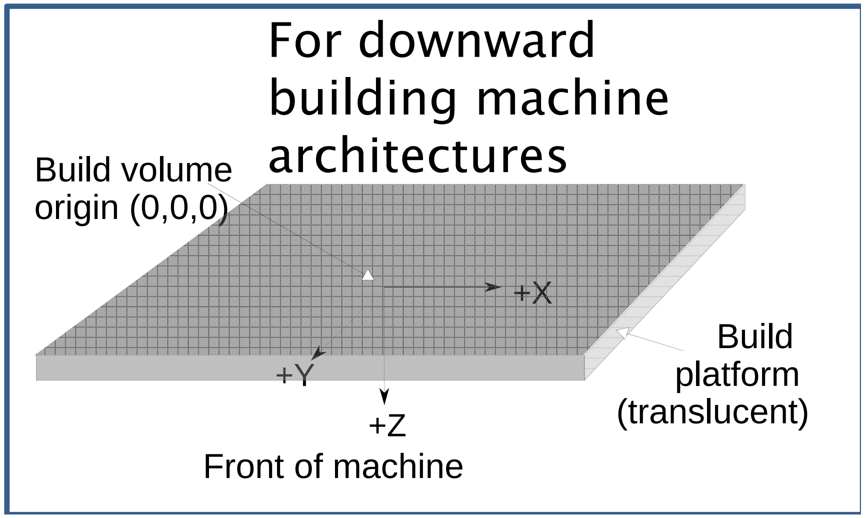
Testing

- Testing Terminology Standard
  - Standardized part orientation and location within a build
  - Based on basic coordinate systems as per ISO 841



Coordinate Systems w.r.t Platforms





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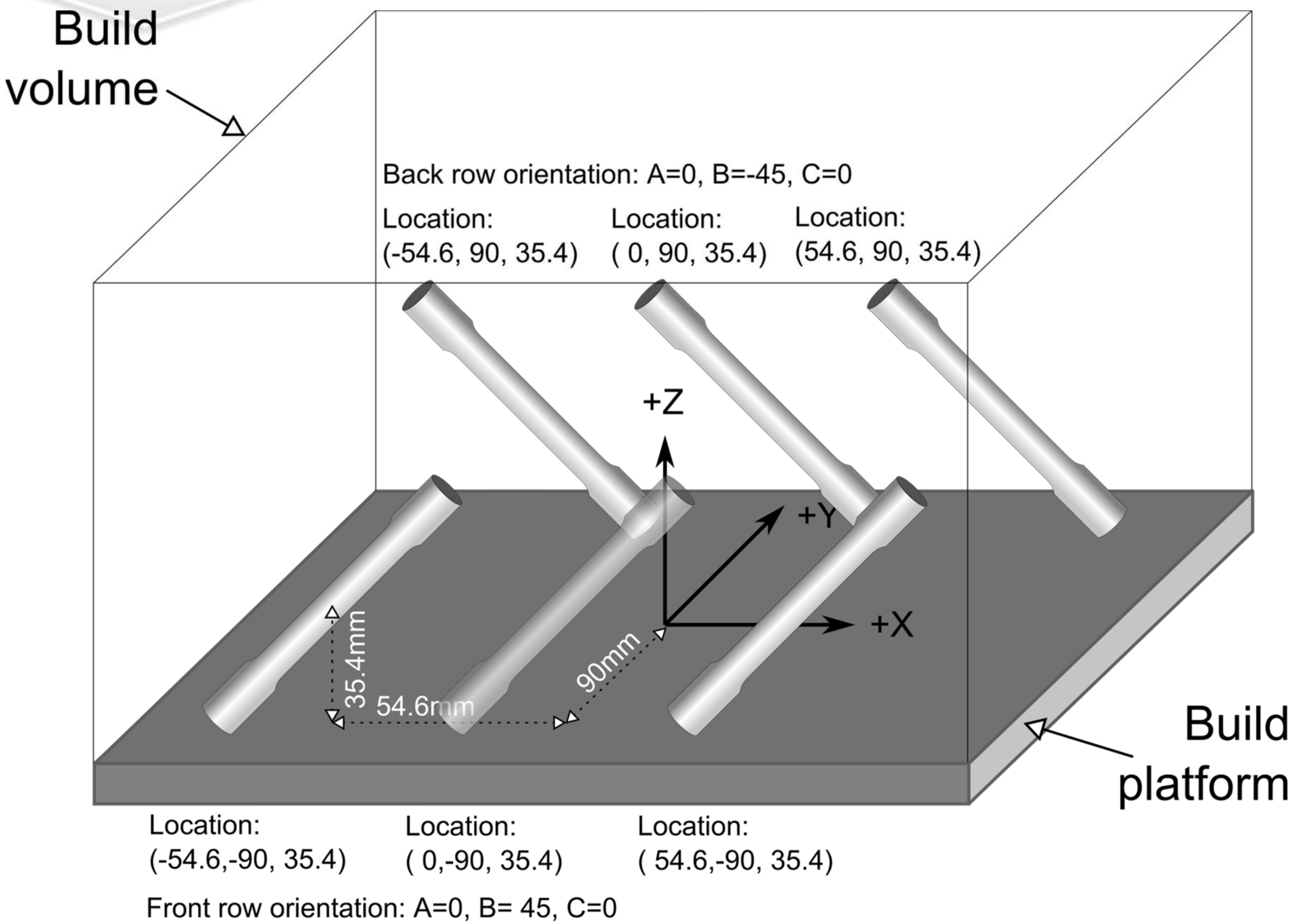
Location and Orientation of Parts



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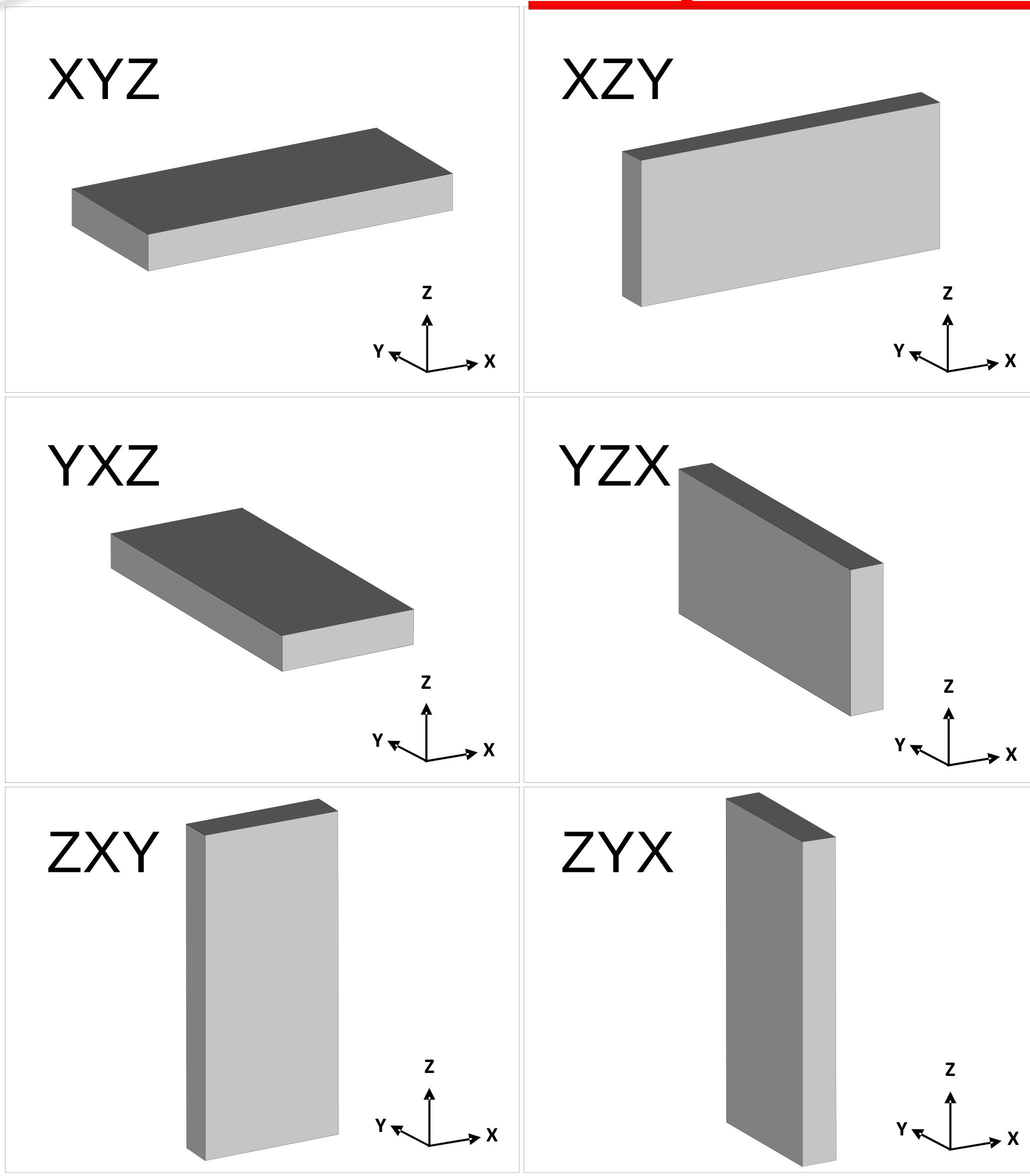
Location and Orientation of Parts with Simplified Notation



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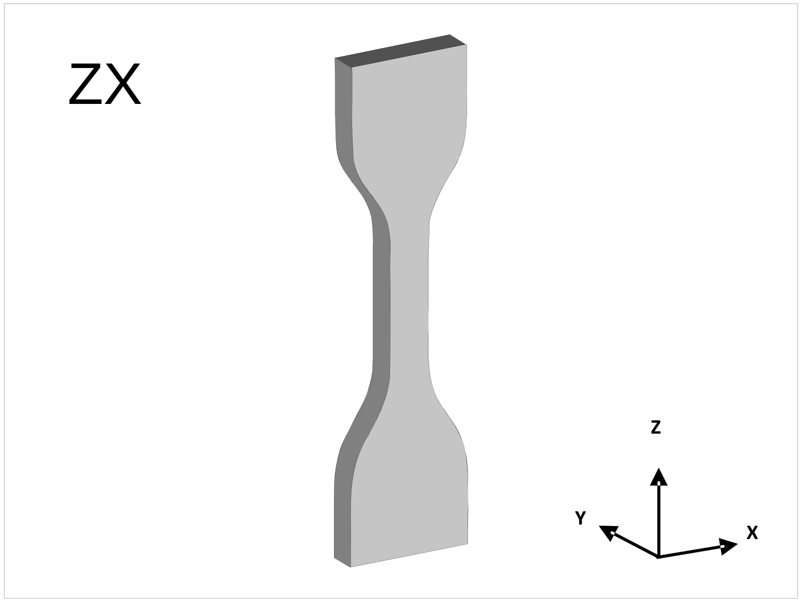
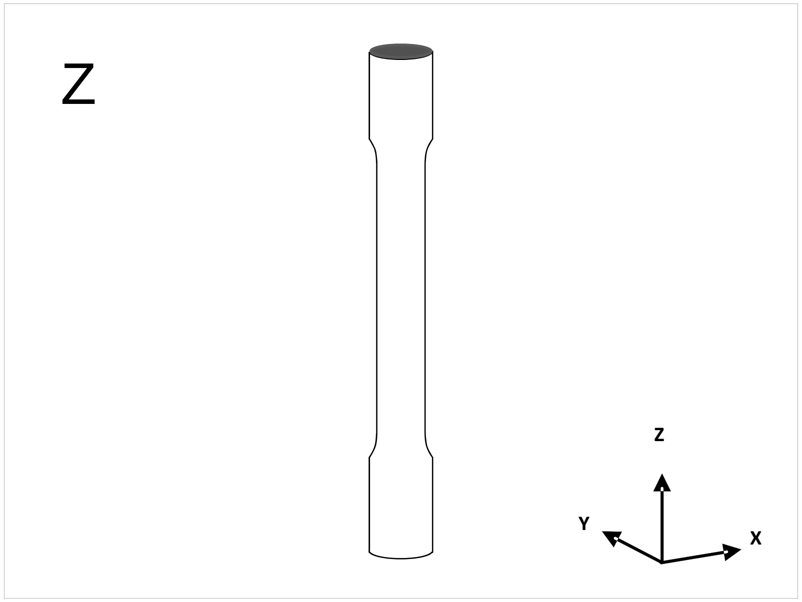
Location and Orientation of Parts with Simplified Notation





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Materials & Processes Standards

- Powder Bed Fusion of Ti 6/4 standard (ASTM F2924)
  - Working on finalizing revision for ISO adoption
    - European members wanted to address alpha prime microstructures & other property considerations
  - Working on other metals
    - Ti 6/4 ELI, IN 718, IN 625, F75 (CoCr), etc.
- Polymer Powder Bed Fusion standard nearing completion for balloting

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US TAG for TC 261

- Coordinating activity with ISO
  - Agreement to co-brand standards
- Working to fast-track adoption of F42 output
  - Terminology
  - Testing Terminology
  - Powder Bed Ti 6/4
  - AMF
- Trying to negotiate the politics of ISO & European priorities

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Key Questions for the Future of AM Standards

- Five years from now, what do we want to have in place for AM standards?
- What impacts will these future standards have on AM users, vendors, and technology providers?
- What steps can we take now to ensure that AM standards achieve the biggest future impact?

Objective Today/Tomorrow: Help determine the priorities needed within ASTM F42 /ISO TC261 for AM standards

Why A Strategic Approach is Needed

- To establish the overall structure and give guidance to task groups, helping with planning and prioritization
- To maximize the impact of the standards by:
  - Preventing overlap and contradiction among F42/TC261 standards
  - Ensuring that future standards work together as an integrated and cohesive set
  - Improving usability and acceptance for future users of all types (from the novice to the expert)

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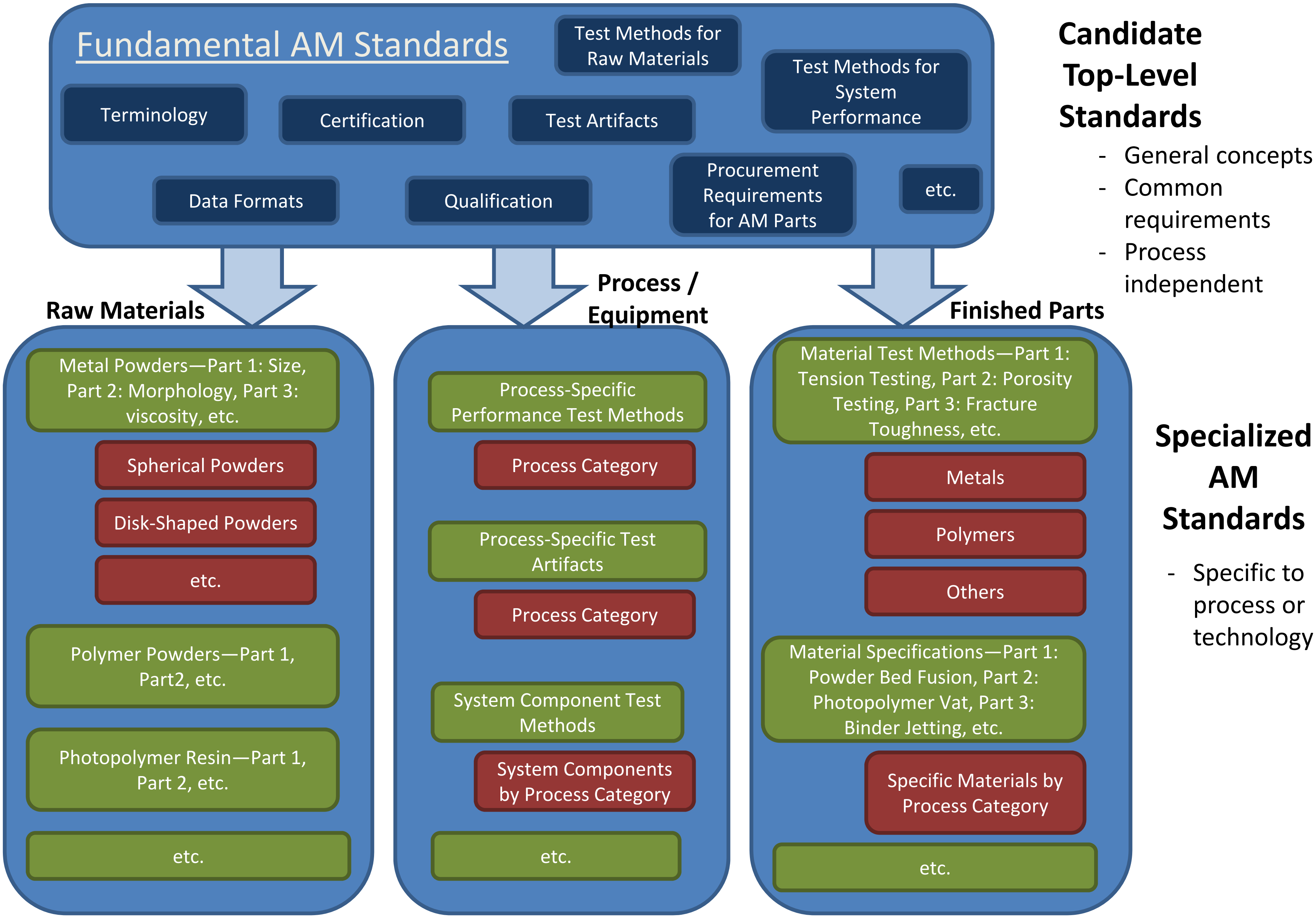
Proposed Strategic Approach

- Augment existing bottom-up approach with a top-down strategic view
  - Keep current progress and momentum intact, but provide structure for logical connections among standards
- Establish a top-level set of fundamental AM standards that address topics and issues common across many AM processes and applications
  - Related sets of specialized AM standards linked to the fundamental AM standards (reference and build on the concepts)
  - Specialized standards to address topics that are specific to a given AM process or technology

NIST Proposed General Structure



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Benefits of Strategic Approach

- Efficient - Reduces potential for redundancies and incompatibilities
- Consistent – reduces potential need for future harmonization of contradictory standards
- Organized – Prioritization and planning of standards development is easier, and relationships between standards are clear
- Includes and supplements current bottom-up approach

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My Hopes for This Meeting

- A Top-Down Roadmap for Standards Development
  - High-level general standards and specific in-depth standard recommendations
- Recommendations for which task groups need to start work now

The Future of International Collaboration?

- We are at a turning point in our industry
  1. We are big enough that people care about us
     - Nationalism is increasingly apparent
     - Financial markets are starting to pay attention to us
  2. Monopolies are disappearing as patents expire
     - New **companies** and new **countries** can compete in the global marketplace
- I see companies and countries trying to lock other companies/countries out of certain AM technologies (and standards development activities).
- Will they succeed? I hope not!
  - "The cat is out of the bag…"

Questions & Comments?

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