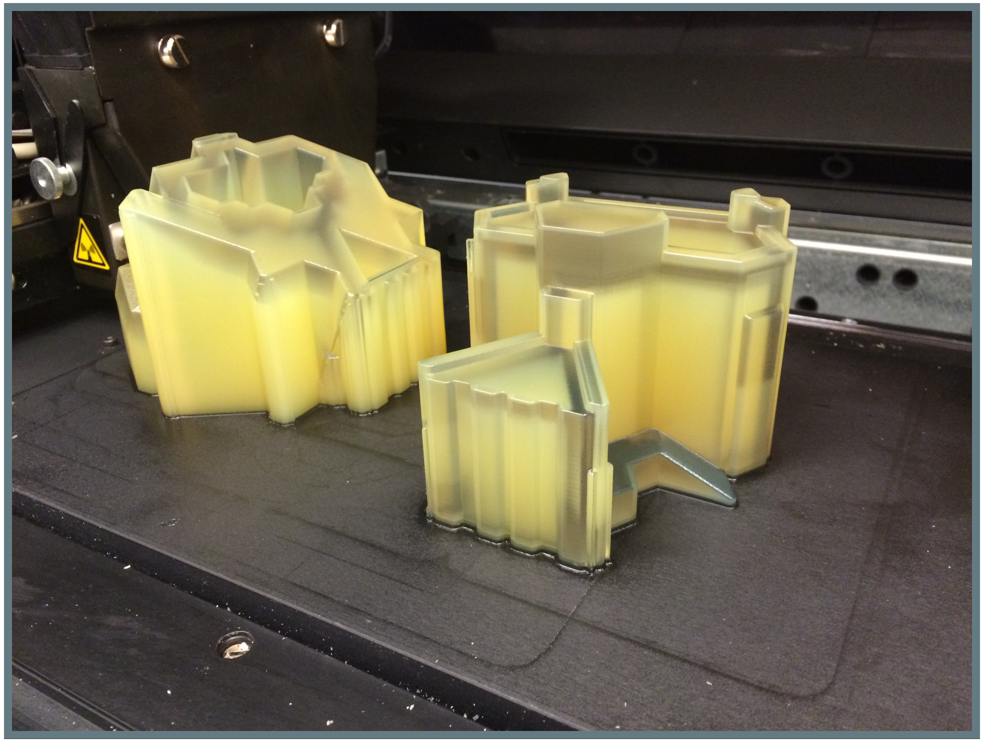
3D PRINTING

DIMITAR JORDANOV, CURTIS MCCORD, LAUREN OLAR & DAWN WALKER

November 26, 2015



3D PRINTING AND ADDITIVE MANUFACTURING (AM)

A family of methods for creating physical objects from virtual representations and digital files of modelled objects or 3D scans.

TECHNIQUES

Most common 3D printing techniques extrude a range of materials using heated nozzles, building up objects a layer at a time:

- Fused Deposition Modelling (FDM)
- Stereolithography (SLA)
- Selective Laser Sintering (SLS)

Early applications primarily rapid prototyping, however matured technique printing is establishing itself in more markets and sectors.

HISTORY

Automated AM developed in the 1960s but not until 1980s and advances in computer-aided design and computerized task management that they were greatly improved.

First 3D printers used SLA technology. FDM was brought into public eye with release of consumer-oriented Thing-o-matic in 2009. SLS development began in the 1990's, though it is considered too dangerous to be used outside of specialized industries.

Denkin released the first consumer printer in 2006. Since then, FlashForge and Autodesk among others, have released SLA printers that fit on a bench and can be supported without highly specialized architectures.

INDUSTRY LANDSCAPE

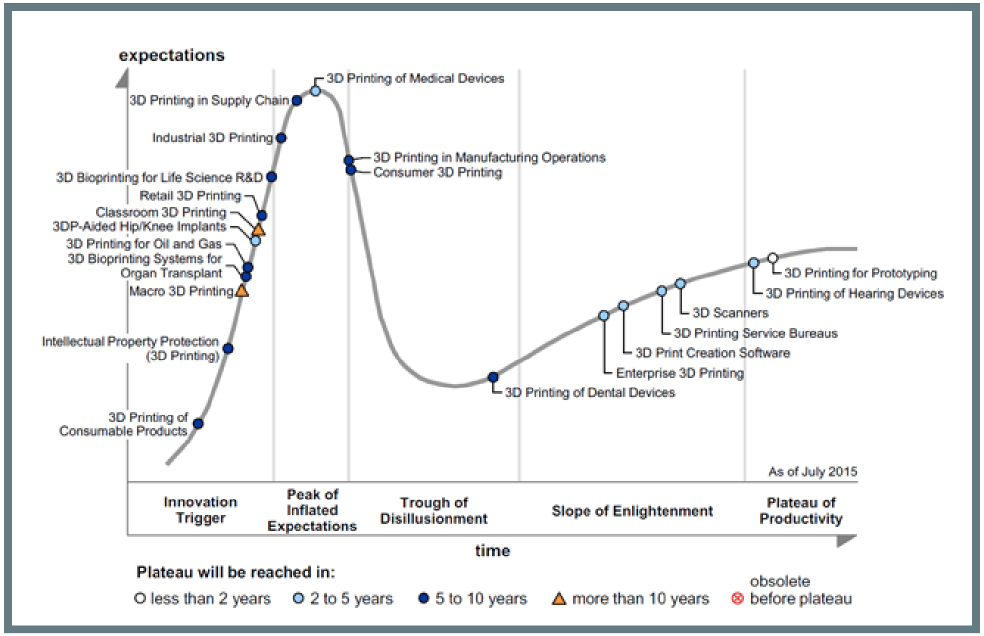
Manufacturing integral process in many sectors, changes resulting from the move to AM has the potential to impact a range of markets.

Market areas where AM techniques are presently established include: aerospace, automotive, health care (medical devices and models), consumer goods, industry applications, as well as research and education.

HYPE

Annual projections of the 3D printing industry at 2020 [Investopedia, 2015]:

GROWTH	REVENUE
31%	$21 billion



BUSINESS PERSPECTIVE

Opportunities exist for reshaping interactions and relationships between businesses and customers.

AM CHARACTERISTICS

- Versatile, on-demand manufacturing process
- Eliminates sunk-cost customization and flexibility
- Allows for design and product line complexity without increasing manufacturing costs
- Reduces production steps and manual labour throughout production [Weller et al., 2015]

MARKETS

Distinction between primary and secondary markets.

Primary Markets:

- Industrial markets comprise 93%
- Clients include large enterprises, generate high business value

Secondary Markets:

- Consumer markets consisting of small residential consumers and 3D printing hobbyists
- Largest 3D printer utilization at 79% [Smithers Pira, 2015]

Further categorizations depend on the application, region or material used.

EMERGING MARKETS

2015 trends for emerging markets include:

- bioprinting (eg. organs)
- aerospace
- space exploration

Emerging markets usually require further technological advances in order to become more prominent.

BUSINESS MODELS

5 Major Business Models

- Enabler for Design Optimization
- Value Add By Customization
- Cost Efficient Production Method
- New Supply Chain Concepts
- Repair by AM / Support Services [Weller et al., 2015]

There are also various emerging models

ENABLER FOR DESIGN OPTIMIZATION

Increases product quality by improving its *performance*, *functionality or aesthetics*. This results in a reduction of time required for product development, along with reducing time-to-customer.

✈**Example:** Airbus included over 1000 3D printed parts into one of their recent airplane models in order to decrease the airplane's mass and thereby increasing overall performance [Lutter-Günther et al., 2015]

VALUE ADD BY CUSTOMIZATION

Enables customers to request one-off, rapidly-prototyped manufacturing for individual, personalized parts. Offers reduced time-to-customer as well.

Example: Production of highly-personalized, tissue-based body part / organ replacements using living cells as ink [Ledford, 2015]

COST EFFICIENT PRODUCTION METHOD

Using small-scale / short-run (rapid) manufacturing, customers that require low production volumes can order affordable printing services, thus lowering the required cost.

Minimal price and cost stability are not guaranteed for all volume sizes, but can be found, achieved and routinized

Example: Rotary knobs and timing belt covers - a steep cost drop and stability occurs at about 100-item batches [Ruffo et al., 2007]

NEW SUPPLY CHAIN CONCEPTS

Fragmented, decentralized production - leveraging remote production sites when lacking local production tools.

This lowers distribution efforts, namely *packaging, transportation, and customs expenses, as well as time-to-consumer*

Example: 3D printing machinery onboard US Navy aircraft carriers to manufacture parts for UAVs on demand, but this creates security issues [Lang, 2013]

REPAIR BY AM / SUPPORT SERVICES

Support service for businesses whose machinery requires maintenance through part replacements.

Reduces maintenance costs and operational down-times, since any replacement part are manufactured at the point of demand

Example: Siemens Energy uses SLS to repair their machinery on site [Lutter-Günther et al., 2015]

EMERGING MODELS

- Open-source and free resources
- Open-source model repositories gaining traction
- Makerspaces
- 3D printing marketplaces and communities
- New categories of AM service providers
- 3D scanning and printing in retail
- Established manufacturers and brands entering AM market
- Unique collaborations [Wohlers Associates Inc, 2015]

ORGANIZATIONAL PERSPECTIVE

A key consideration in consumer-oriented manufacturing sectors is the product life cycle: a concept used to describe a product from introduction to decline. Current trends are toward a leaner cycle and reduction in product lifespan, forcing companies to innovate with products alongside business and organizational models

MOTIVATIONS

Executives ranked the most important perceived benefits of AM. Key decision points were identified for driving adoption:

1. lean product life cycle: more responsive to market, design and commercial uncertainties
2. product design and delivery: more freedom to explore solutions (e.g. mass customization)
3. tooling and assembly: in fragmented supply chains
4. working capital in inventory: lowering capital tied in inventory increases flexibility [Cohen, 2014; Ahuja et al., 2015]

Goal of AM adoption to remain competitive, responding primarily to rivalries and threats from substitute products.

INTERACTIONS AND RELATIONSHIPS

Currently a lack of “end-to-end integration across teams,” in the organization. Strategies to build integration include [Cohen, 2014]:

- instituting champions for the technology
- empowering the product design team through support and education
- creating alignment with procurement, design and production
- re-investigating quality assurance (QA) protocols and how the QA team interacts with earlier stages of production

ORGANIZATIONAL ROLES AND UNITS

AM requires rethinking organization design ideologies and processes, potentially impacting many roles and units: *Procurement*, *tooling*, *design*, *production*, *quality control (testing)*, *repaire and maintenance as well as project management roles* could all face changes to their work. Legal departments and human resources would tackle new regulatory and occupational (including safety) concerns requiring their expertise.

Production especially will see the nature of their work change dramatically: material management, job setup, task management, cleaning and recycling are all new considerations.

INFORMATION PERSPECTIVE

The information perspective centers upon the computer aided design (CAD) packages used to model objects that will be 3D printed. Given this is a unique situation where digital information is transformed into a material object, there are digital as well as physical concerns to pay attention to [Mavri, 2015].

PHYSICAL CONSIDERATIONS

The 3D model being created needs to be precise and unambiguous. If it is lacking in either, the physical object will come out with errors or be impossible to be printed [Balc, 2001]

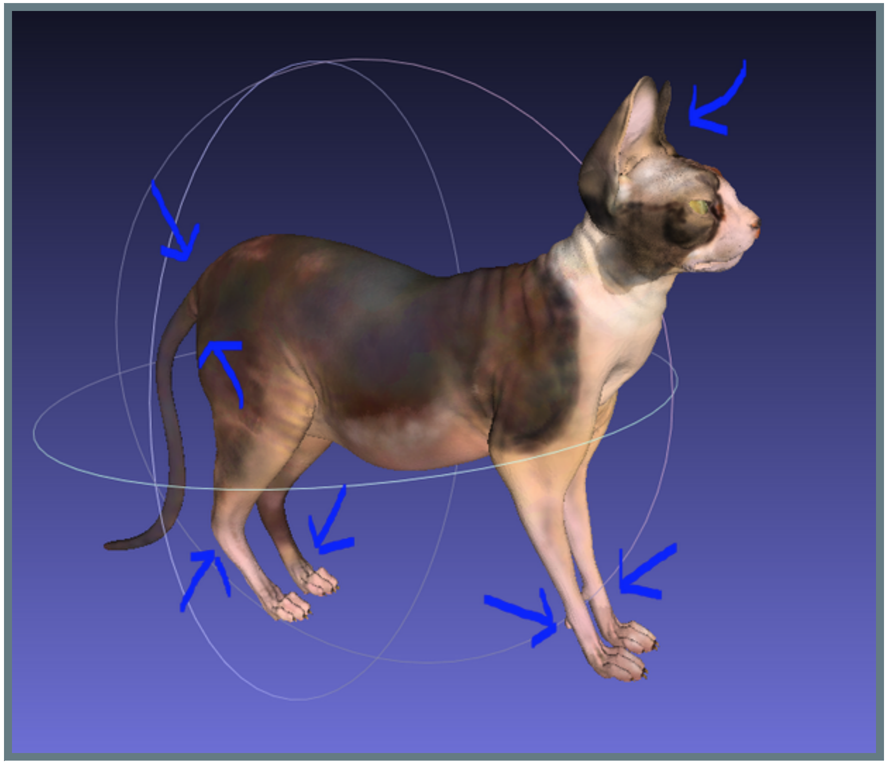
SIZE

Object needs to fit the printer and the needs of the user

- Size of the printer and what is to be printed
- For interlocking objects, consider how they fit together
- Size of the object the model will be used with/on (for example, jewelry) [Berenhaus, 2015]

APPENDAGES

If an object contains areas that are vulnerable during the printing process, consideration must be given on how to alleviate the risk of a part breaking off. Users must give thought to the pose of the object, as well as consider adding supports to certain areas [Berenhaus, 2015]



http://www.shapeways.com/tutorials/how-to-prepare-your-render-animation-model-for-3d-printing

COST

Some materials are very expensive to print. Depending on what material is being used to create the object, users may want make their models hollower or thinner what they can in order to save on the material [Berenhaus, 2015]

FILE CONSIDERATIONS

On top of the physical consideration, user's need to think about certain aspects of the CAD files themselves.

ORIGIN

Many organizations will create models to print the objects they wish to manufacture. However, anybody with access to 3D modelling software has the capability to create one. Online communities such as Shapeways allow users to upload their own design to their website and they will print and ship the item to the user.

RELIABILITY / TRUSTWORTHINESS

This aspect will depend on the origin of the model

- Most likely accurate when created within organization
- If created by amateur and uploaded, may not be very reliable
- Uploaded models may be malformed and unsuitable for printing

PRIVACY / SECURITY

The biggest privacy issue with 3D printing currently is that printers do not care what they are printing, they will print any appropriate file they are given. There is always the chance in the future that 3D printers will equip digital rights management controls to ensure users are not printing items that are protected. If an organization is utilizing 3D printers they need to look into ways to keep their files secured and protected. Examples would be encrypting the files, or circulating them through a secure server [Baker, 2015].

INTEROPERABILITY

Applications that are used to view and construct 3D models, scan objects, and manipulate printing configurations work in a variety of formats, each offering different metadata structure:

- Some use custom file formats
- stereolithographs **.stl** are the common standard
- **.stl** often parsed into **.gcode** format

APPLICATION SYSTEM PERSPECTIVE

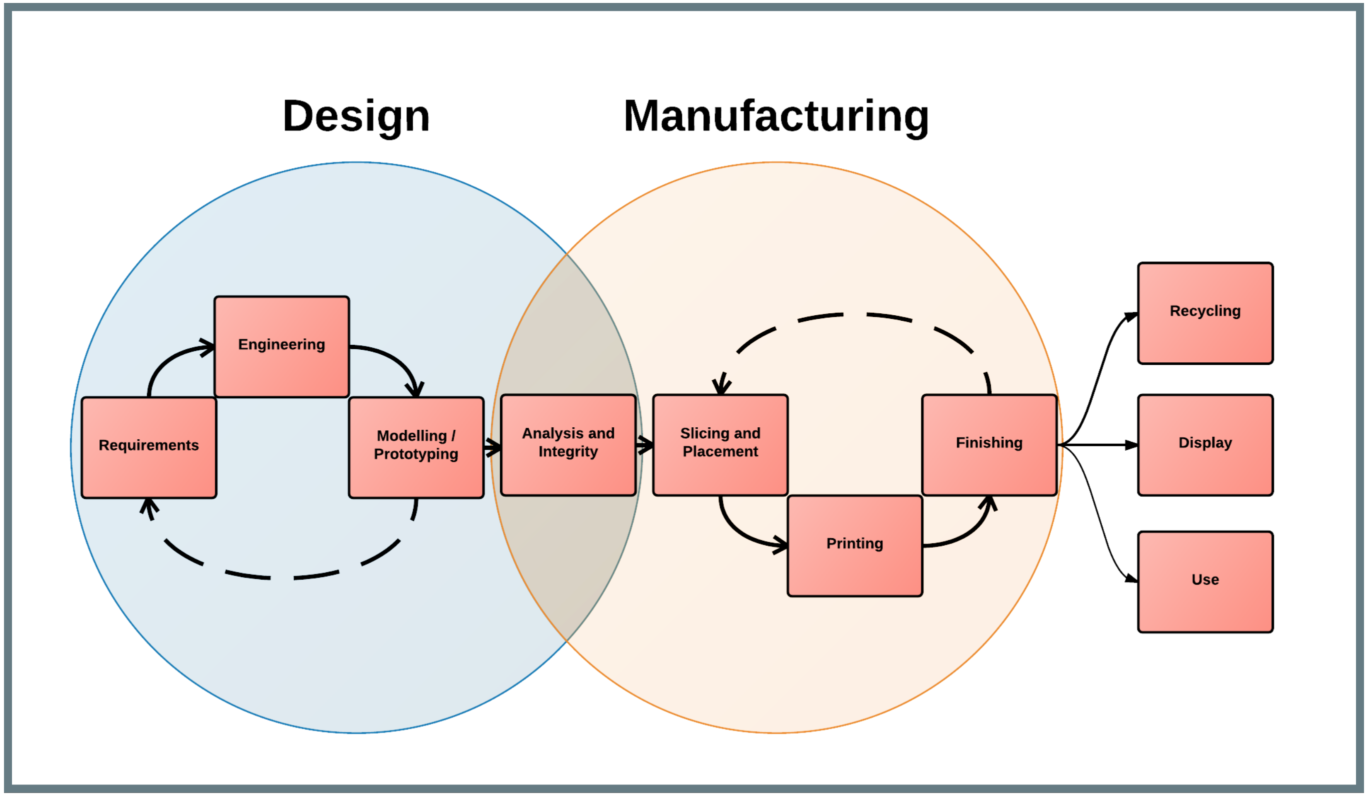
"Even when a design has been optimized specifically for the process, it often takes dozens of tries before a functional part comes out of the printer. And the process of troubleshooting a failed build–even at the most advanced ... shops in the world–still involves a lot of trial and error."

[Wright, 2015]

"3D Printing Titanium and the Bin of Broken Dreams"

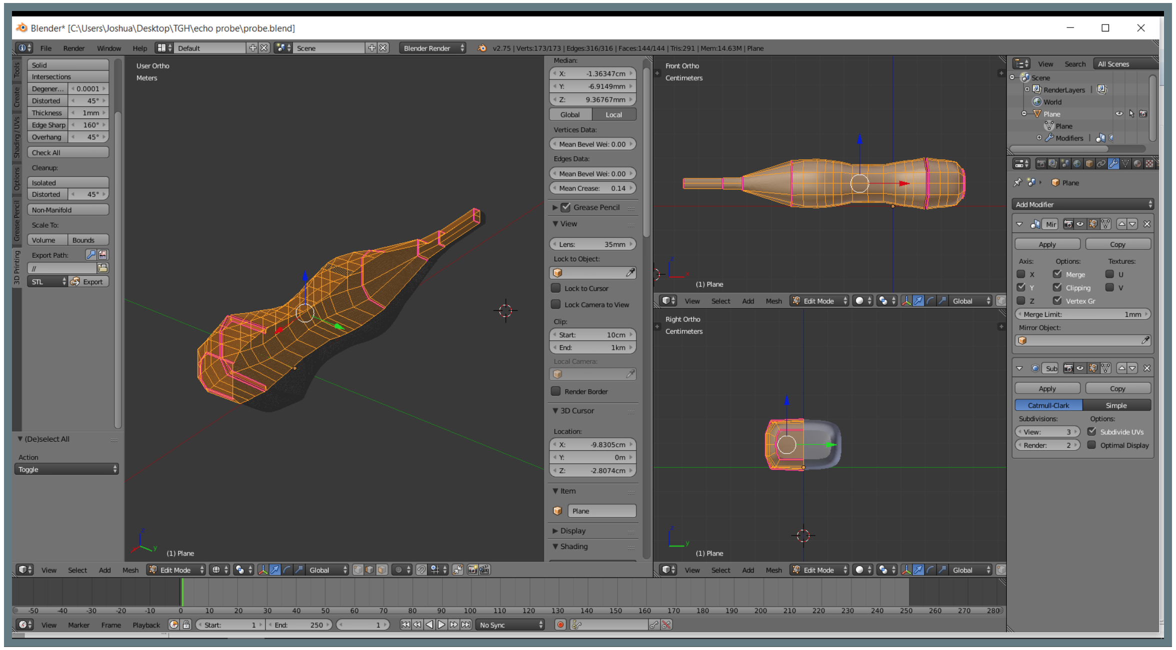
CORE FUNCTIONALITIES

3D printing requires a diverse ecosystem of information, labour, workflows, and applications. Although models can be acquired that are ready-made for printing, there is, in fact, a more expanded, general process that describes the core functionalities of a 3D printing 'system', which can include dimensions of both design and manufacturing.

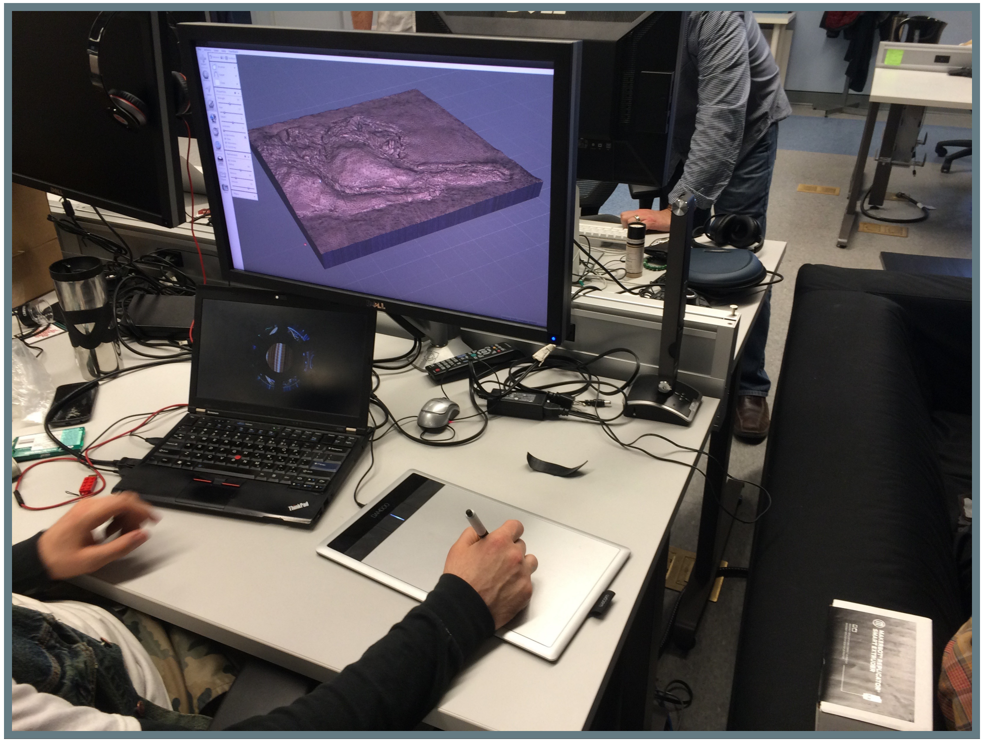


3D MODELLING

Depending on their existing design processes, organizations will have various needs when it comes to integrating 3D printing *qua* manufacturing process. There is already an established ecosystem of modelling applications that are integratable with a 3D printing workflow. The type of modelling software selected affects not only the software architecture, but the price, capabilities, and the amount of training needed to operate them.



Parametric modelling softwares such as Solidworks, Autodesk Fusion or Blender (shown above) allow users to create objects by changing dimensions or by extruding faces. Some of these programmes have been mainstays of the modelling craft for years, and have steep learning curves. They are very complex, and allow many parts to be represented in assemblies.



Direct modelling softwares, such as MeshMixer use brushes to sculpt or shape objects directly. These softwares may be unsuitable for modelling large part assemblies but might also be the best option for repairing found models or 3D scans.

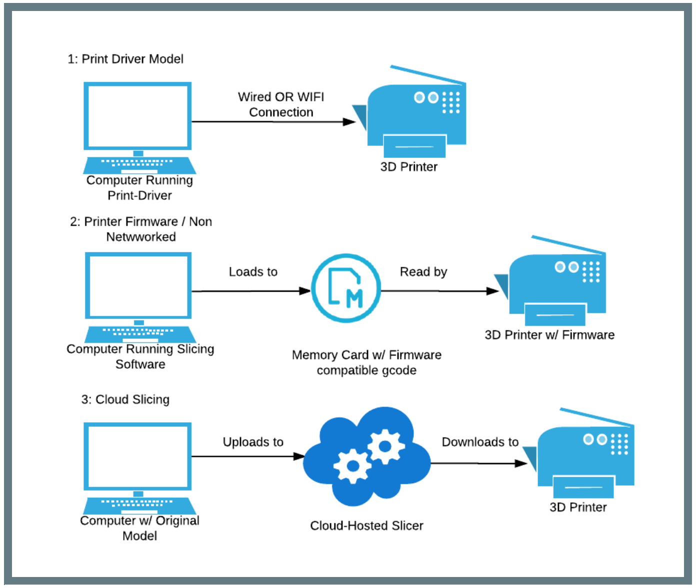
SLICING

Slicing is the process of taking a 3D model and preparing it for printing by making it readable for 3D printers (.gcode). Slicers assist users in configuring their models for optimal printing by calculating material usage and cost, as well as configuring attributes such as:

- Nozzle, bed and chamber temperature
- Speed of nozzle movement
- Number of outer walls (shells) on model
- Amount of material in model interior (infill)
- Orientation of model on bed
- Supports for printing complex geometries

PRINTING PROCESSES: PRINT DRIVERS AND NETWORKING

Various architectures exist for transferring a sliced 3D model to a printer for printing [RepRap, 2015].

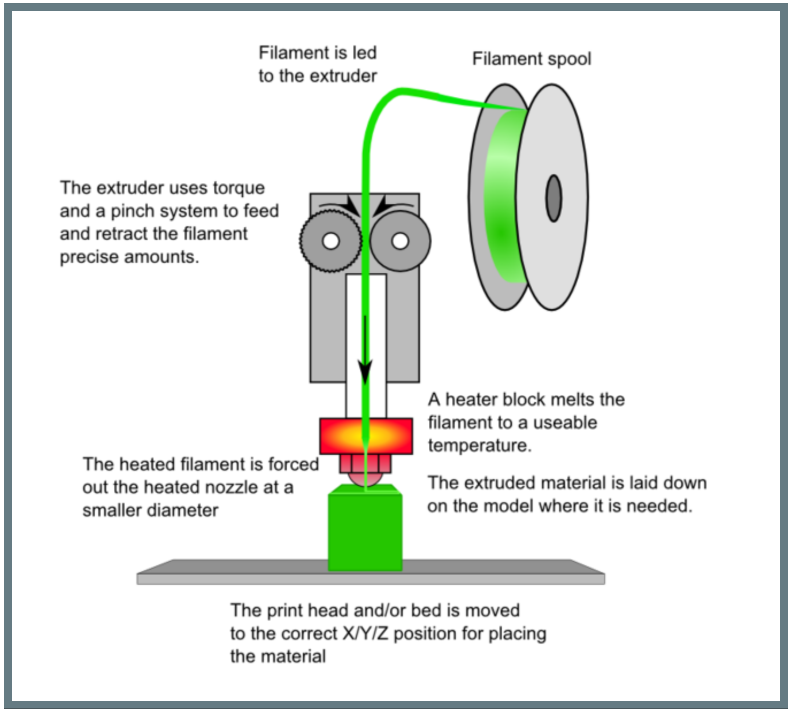


Architecture types from [Ratto and Doell, 2015]

Cloud-based have users upload models to cloud-based applications, specify parameters, and stream directly to a 3D printer, mititgating computational costs of processing complex models [Autodesk, 2015, The Printer Working Group, 2015].

TYPES OF 3D PRINTERS

FUSED DEPOSITION MODELLING (FDM)

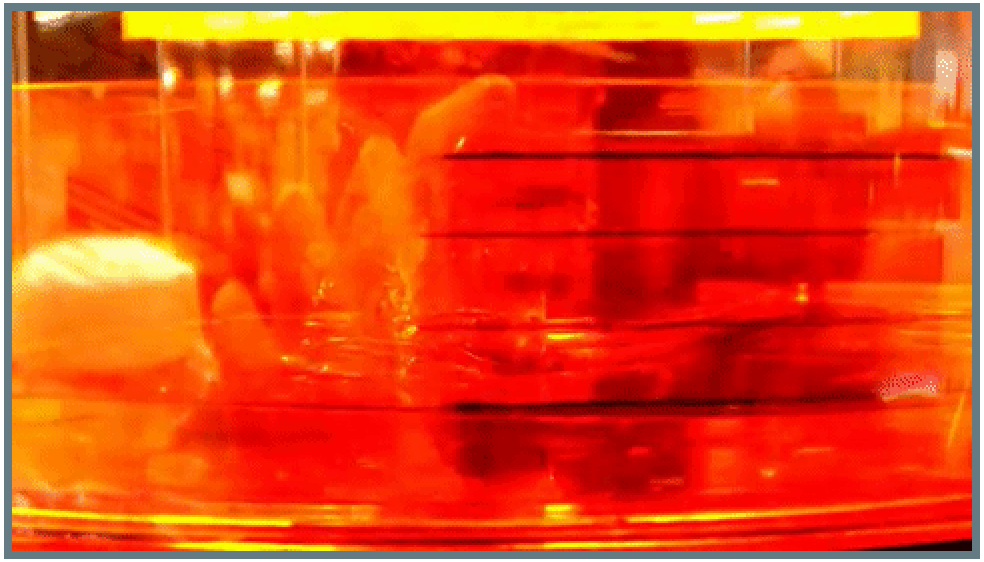


FDM printing is the most widely known and consumer-acessible type of 3D printing. FDM printing is ideal for printing a variety of conventional and experimental materials, depending on the capabilities of the printer itself. Basic printers often print plastics like PLA or ABS, which are durable and suitable for a wide range of applications. With a heated bed or chamber, printers can also print materials like wood-composite, nylon, polycarbonate, and carbon-fiber reinforced materials.

Image licensed through Creative Commons, source: http://reprap.org/wiki/Fused_filament_fabrication.

STEREOLITHOGRAPHY (SLA)

SLA printing uses a laser or UV light to cure a photosensitive liquid resin (a prepolymer) into a coherent polymer structure isomorphic to a 3D model [Bàrtolo, 2011]. SLA has the advantage of being able to print complex geometries in high resolution, giving it excellent potential in the medical and dental modelling fields, as well as an established role in rapid prototyping [Cline, 2013]. SLA is now also becoming increasingly available to consumers [Anusci, 2015].



SELECTIVE LASER SINTERING (SLS)

SLS uses a high powered laser to harden a uniform material from a reservoir of powdered material or sprays materials ranging from plastic to metal out of a nozzle direction into the path of the laser [Wright, 2015]. SLS can be used to print very complex parts in a variety of exoitc materials, like metal. In the aerospace and automotive industry, SLS can be used to create small numbers of parts within very specific tolerances [Munchow, 2015].

EVOLUTION AND THE FUTURE OF 3D PRINTING

Barriers to entry are lowering while quality and reliability of production is rising.

- **New Materials** will expand the range of applications for 3D printed parts, from Aerospace [Boeing, 2015], to nano-printing [Smith, 2015], and perhaps even organic material (bio-printing) [Organovo, 2015].
- **Job-Management Applications** will enable the coordination of multiple printers simultaneously. Type A machines and Straysys currently markets the Print Pod- a system of interconnected 3D printers that can handle large assemblies or managed workflows [Type A, 2015; Crouse, 2015].

Type A Machines, 2015
http://www.typeamachines.com/blog/cost-effective-3d-printing-thanks-to-mass-customization

OPEN SOURCE 3D PRINTING

Robust communities of practise include makers, designers, researchers, etc, create powerful Free and Open Source solutions available under GNU GPL lisences:

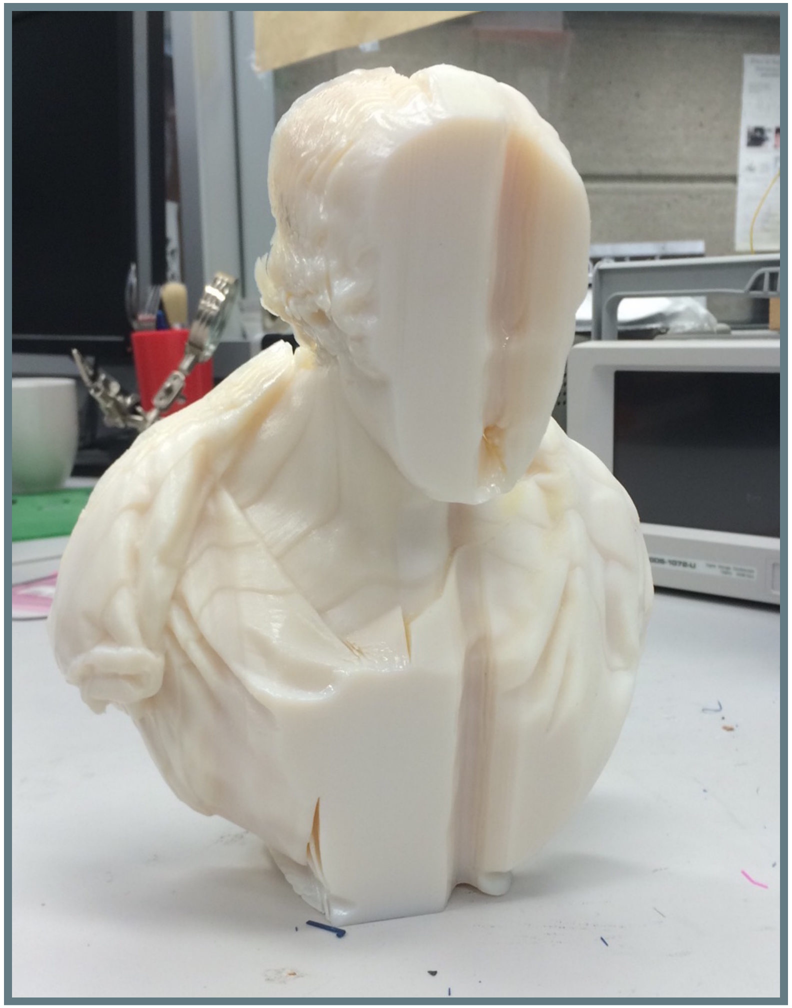
- **Modelling programs** include Blender, OPENSCAD and MESHMIXER
- **Slicers** include Slic3r, Cura, Simplify 3D
- **Companies** like Autodesk often work with their users to refine their products using open source licences
- Aleph Industries TAZ LULZBOT **printers** (below) are certified "free" by the Free Foftware Foundation [Lulzbot, 2015]

REQUIREMENTS & DESIGN

MODELLING LANGUAGES

There are a number of steps within a 3D printing work-flow that can reliably be expected to arise, including steps like mesh repair, slicing, placement, and setting parameters. While these, in a sense *could* be reflected by BPMN models, it should be noted that this would obscure a lot of the skilled heuristic work within these subprocesses. Data flow diagrams would offer an interesting, though very distant model of the mediation of data throughout a 3D printing process. We must at all points, however, recall that there is a large amount of feedback between printer and operator which is obscured by rigorous modelling languages, though they may be useful for training and documentation.

SPECIAL CHALLENGES



THROUGHPUT

Including modelling, prep and print time, and accounting some objects may take hours or days to create. Organizations need to be aware of this timeliness and consider if the amount of objects they need vs how many printers they can acquire is reasonable in order to adopt 3D printing into their processes.

SCALABILITY

Some 3D designs do not scale to traditionally manufacturing. What may work out in a 3d printed prototype may not always scale to manufacturing ideals when geometry and number of parts needed are considered.

EXTENSIBILITY

Open source 3D printers can be modified to increase nozzle size, to accept more extruder heads, or to print in different materials. In some cases, they can even be rebuilt to print in larger volumes. Both the hardware and software of simple FOSS FDM machines is extremely modular. Proprietary systems do not age as well, and will need to be replaced when their original functionality no longer serves firm needs.

USABILITY

Printers can take practise to calibrate and may break down. Operators must be prepared to get to know the mechanics of their software and printers, and to keep the printers maintained. Learning to print requires taking on a new mindset to object creation.

INTEROPERABILITY

Having an interoperable hardware and software environment is essential to 3D printing. However, with either proprietary or FOSS equipment, this is generally an easy standard to attain, thanks to widespread use of .stl and .gcode formats

RELIABILITY

Models can fail in many ways, from inter-layer adhesion issues, improper calibration, material feed malfunction, temperature being off, or the slicing may have failed. Troubleshooting these problems and getting 3D printers into a good work-flow is the task of skilled operators, and can only be accomplished with research, technique and time!

STANDARDS & GUIDELINES

Currently nascent, either local to organization, or derived ad hoc from file format and software requirements [Brewster, 2013]

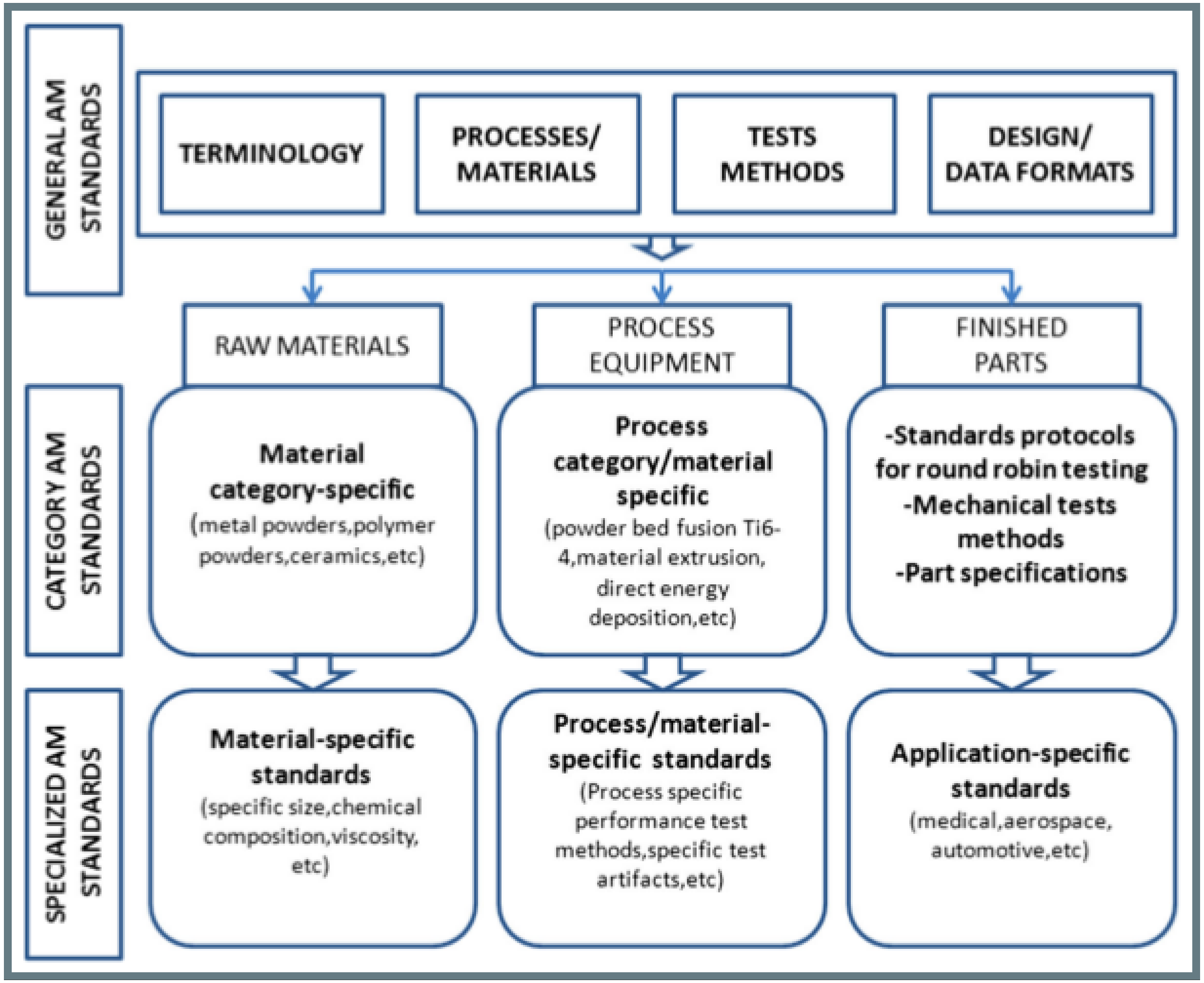
Informality of standards seen a key barrier to widespread adoption [Monzón et al., 2015]

INDUSTRY STANDARDS, GUIDELINES, AND BEST PRACTISES

More efforts are being formed to develop and codify best practises, primarily driven by:

- **ASTM** International (previously American Society for Testing and Materials)
- International Organization for Standardization (**ISO**)

Government agencies trying to encourage development of measurements and standards through grants and policy (e.g. **NIST** recently awarding $7.4 million in grants [NIST, 2013].



Hierarchy of AM standards by ASTM and ISO

[Monzón et al., 2015]

RECENT TRENDS

- **3MF Industry Consortium** (2015)with printer manufacturers formed to release a 3D printing format specification (3MF) [3MF Consortium, 2015]
- **Printer Working Group** (2015) White Paper on standardizing 3D Printing using current PWG Semantic Model [The Printer Working Group, 2015]
- **ISO** (2011) Committee TC 261 for AM with four working groups (WG1-WG4)
- **ASTM International** technical committees on AM working on standards (F42, F42.01, F42.04, F42.05)
- **UL (Underwriters Laboratories)** (2015) safety-oriented "3D Printing [AM] Equipment Compliance [Guidelines]" and Medical Equipment guidelines [UL, 2015, Wikipedia, 2015]

REGULATORY AND LEGAL CONSIDERATIONS

Challenging landscape because *3D printing technology development is not centralized to one country*. United States hosts many key companies, manufacturers and other organizations, but others in South East Asia and Europe.

Already *regulated markets and safety-critical sectors* (e.g. aerospace and health care) have to receive additional approvals from industry regulators (e.g FAA and FDA). [Wright, 2014].

Material *Intellectual Property rights*: design protection right, copyright, patent and trademark are enforced through increasingly harmonized laws under the Trans-Pacific Partnership (TPP) [Bradshaw et al., 2010, Depoorter, 2014]

PATENTS

Surge in IP proliferation from 2010 on. Top 20 companies holding patents reveals a mix of:

- ‘direct entrants’ (Stratasys, 3D Systems Inc., Objet Ltd.)
- established companies diversifying into the industry (Hewlett-Packard Co, IBM, Xerox)
- research institutions (MIT, University of Northwestern)

Has been recent aggressive acquisitions and portfolio consolidation primarily by Stratasys and 3D Systems Inc.

Despite this, still distribution of patent holders across the range of application areas, materials and technologies

ASSOCIATIONS AND USER GROUPS

Oriented toward industry members including manufacturers, designers and resellers along- side scientific research organizations:

- Additive Manufacturing Association (**AMA in the VDMA**)
- Association for Manufacturing Additive Technology Group (**AMG**)
- 3D Printing Association (**3DPA**)

Education and Users including owners and operators of additive manufacturing equipment:

- Additive Manufacturing Users Group (**AMUG**)

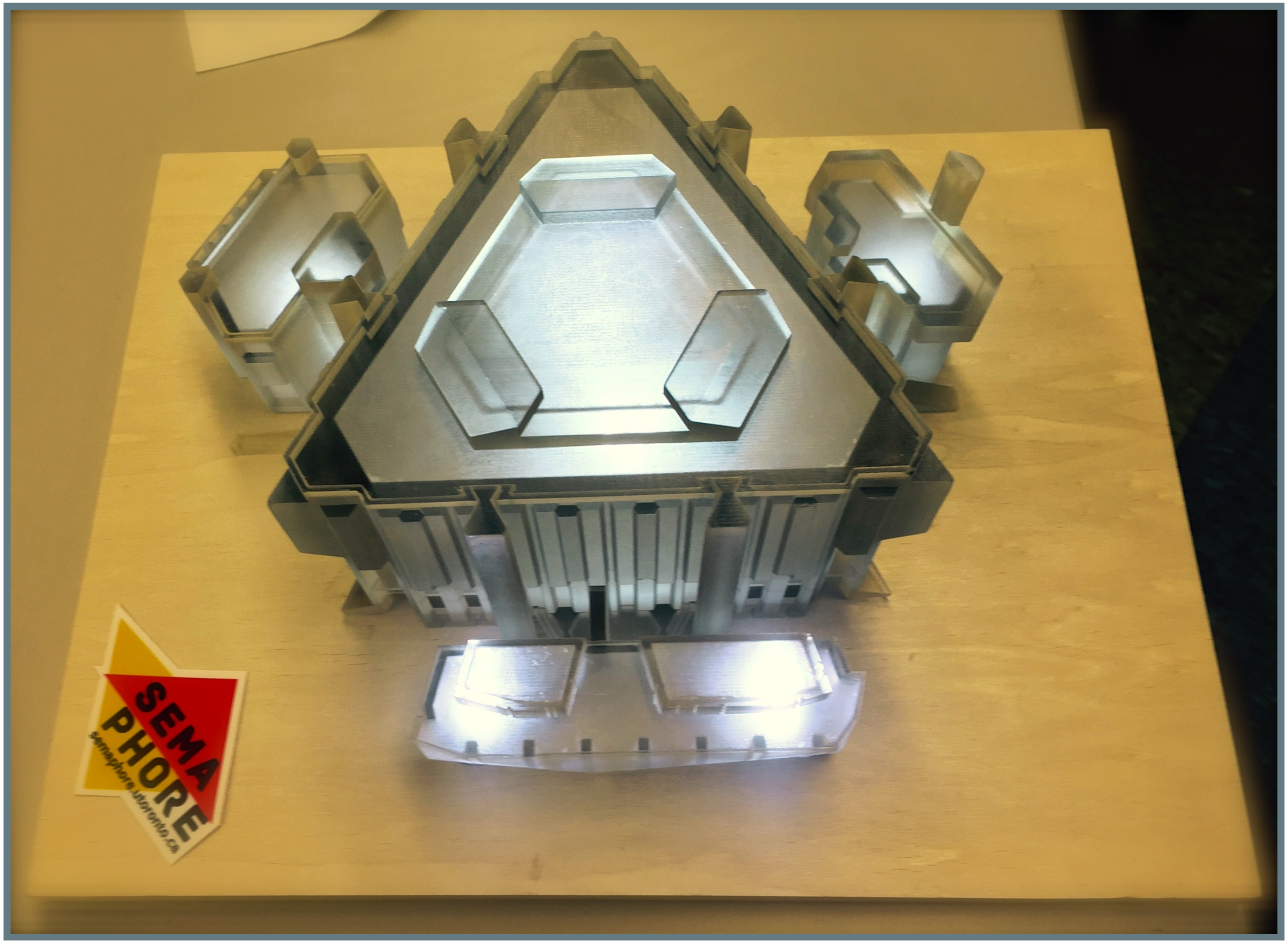
For consumer equipment, meetups and hackerspaces continue to be popular ways to interact with 3D printers.

GOVERNMENT SUPPORT

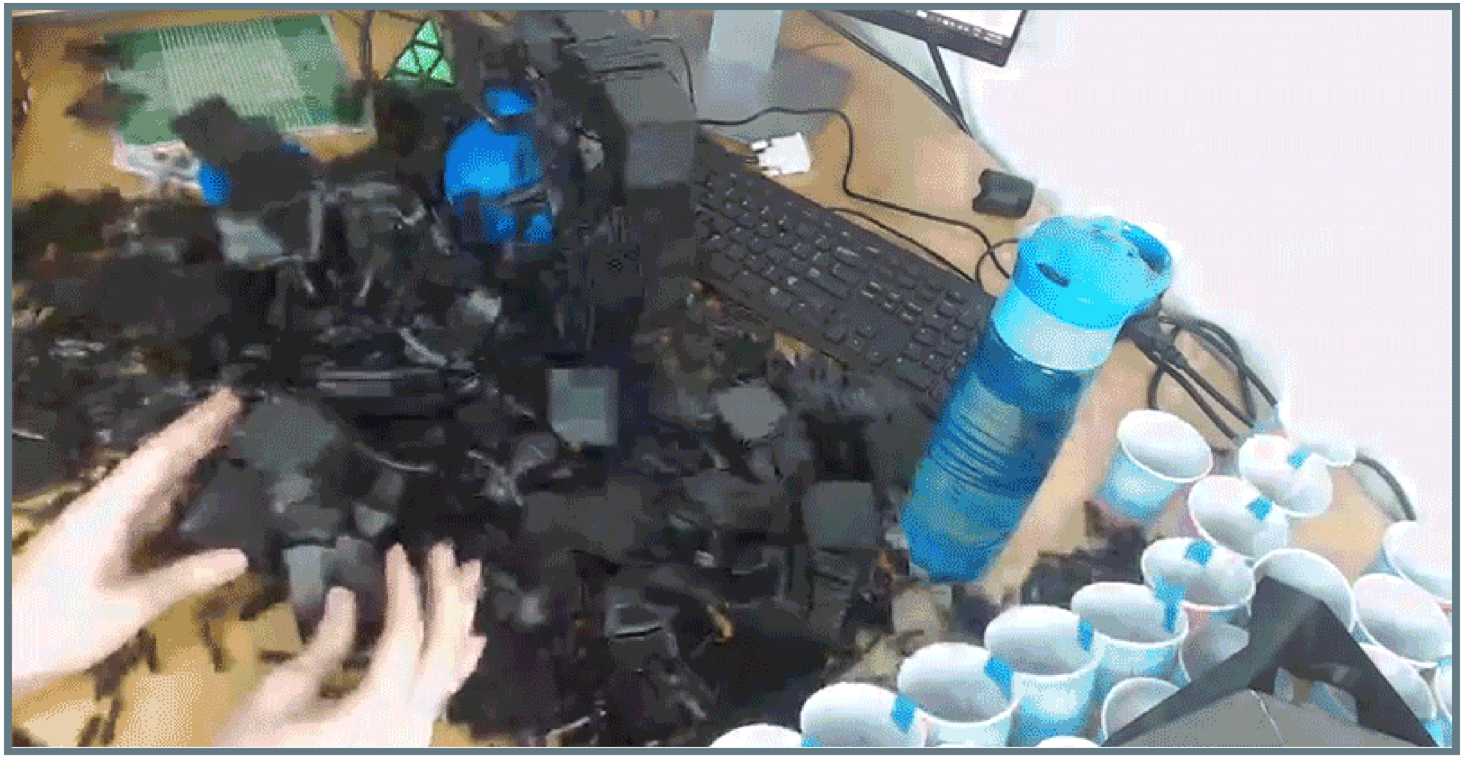
In United States significant support has come from the Federal Government since 2012 through the National Network for Manufacturing Innovation (NNMI) and America Makes, a national accelerator for additive manufacturing and 3D printing:

> *"linking and integrating [small- and medium-sized, or startup] companies with existing public, private, or not-for-profit industrial and economic development resources, and business incubators"*

END



QUESTIONS?



REFERENCES

[3MF Consortium, 2015] 3MF Consortium (2015). 3mf consortium. [Online; accessed 17- October-2015].

[Ahuja et al., 2015] Ahuja, B., Karg, M., and Schmidt, M. (2015). Additive manufacturing in production: challenges and opportunities. In SPIE LASE, pages 935304–935304. International Society for Optics and Photonics.

[Anusci, 2015] Anusci, V. (2015). These are the best SLA 3d printers you can buy in 2015. [Online; accessed 20-October-2015].

[Autodesk, 2015] Autodesk (2015). Spark. [Online; accessed 19-October-2015] .

[Baker, 2015] Baker, P. (2015). 3d printers: It's next great data challenge. [Online; accessed19-October-2015]

[Balc, 2001] Balc, N., C. R. (2001). From cad and rp to innovative manufacturing. Computing and Solutions in Manufacturing Engineering. [Online; accessed 18-October-2015].

[Bàrtolo, 2011] B`artolo, P. J. (2011). Stereolithographic processes. In Bàrtolo, P. J., editor, Stereolithography, pages 1–36. Springer US. [Online; accessed 20-October-2015]

[Berenhaus, 2015] Berenhaus, L. (2015). How to prepare your render/animation model for3d printing - part 1 of 2.

[Boeing, 2015] Boeing (2015). Boeing: Lightest. metal. ever. [Online; accessed 16-October- 2015].

[Bradshaw et al., 2010] Bradshaw, S., Bowyer, A., and Haufe, P. (2010). The intellectual property implications of low-cost 3d printing. SCRIPTed, 7(1). [Online; accessed 17- October-2015].

[Brewster, 2013] Brewster, S. (2013). Can 3d printing avoid a napster moment? [Online; accessed 17-October-2015].

[Cline, 2013] Cline, J. (2013). Stereolithography (SLA). [Online; accessed 20-October-2015].

[Cohen, 2014] Cohen, D. L. (2014). Fostering mainstream adoption of industrial 3d printing: Understanding the benefits and promoting organizational readiness. 3D Printing and Additive Manufacturing, 1(2):62–69.

[Crouse, 2015] Crouse, M. (2015). Stratasys to display 'factory of the future' tech. [Online; accessed 26-October-2015].

[Depoorter, 2014] Depoorter, B. (2014). Intellectual property infringements & 3d printing: Decentralized piracy. Hastings Law Journal, 65:1483–1493. [Online; accessed 17-October- 2015].

[Lang, 2013] Lang, C. (2013). Nasa, the navy to streamline supply chains with 3d printers. [Online; accessed 26-October-2015]

[Ledford, 2015] Ledford, H. (2015). The printed organs coming to a body near you. [Online; accessed 26-October-2015].
[Lulzbot, 2015] Lulzbot (2015). Free software for 3d printing. [Online; accessed 19-October- 2015].
[Lutter-Günther et al., 2015] Lutter-Gu ¨nther, M., Seidel, C., Kamps, T., and Reinhart, G. (2015). Implementation of additive manufacturing business models. Applied Mechanics and Materials, 794:547–554.
[Monzón et al., 2015] Monzoón, M., Ortega, Z., Martínez, A., and Ortega, F. (2015). Standardization in additive manufacturing: activities carried out by international organizations and projects. The International Journal of Advanced Manufacturing Technology, 76(5-8):1111–1121.
[Mavri, 2015] Mavri, M. (2015). Redesigning a production chain based on 3d printing technology: Process redesign. 22(3):141–147. [Online; accessed 14-October-2015].
[Munchow, 2015] Munchow, J. (2015). Focus on technology: 3d printing, what is it really? part deux. [Online; accessed 14-October-2015].
[NIST, 2013] NIST (2013). NIST awards $7.4 million in grants for additive manufacturing research. [Online; accessed 18-October-2015].
[Organovo, 2015] Organovo (2015). Bioprinting functional human tissue.
[Ratto and Doell, 2015] Ratto, M. and Doell, M. (2015). Interview on 3d printing.
[Ruffo et al., 2007] Ruffo, M., Tuck, C., and Hague, R. (2007). Make or buy analysis for rapid manufacturing. Rapid Prototyping Journal, 13(1):23–29.
[RepRap, 2015] RepRap (2015). List of firmware. [Online; accessed 19-October-2015]
[Smith, 2015] Smith, R. (2015). 5 incredible trends that will shape our 3d printed future. [Online; accessed 24-October-2015].
[Smithers Pira, 2015] Smithers Pira (2015). Global market for 3d printing expected to reach over $49 billion by 2025.
[The Printer Working Group, 2015] The Printer Working Group (2015). 3d printing. [On- line; accessed 17-October-2015].
[Type A, 2015] Type A (2015). Print Pod.
[UL, 2015] UL (2015). Additive manufacturing. [Online; accessed 18-October-2015].
[Weller et al., 2015] Weller, C., Kleer, R., and Piller, F. T. (2015). Economic implications of 3d printing: Market structure models in light of additive manufacturing revisited. International Journal of Production Economics, 164:43–56.
[Wohlers Associates, Inc., 2015] Wohlers Associates, Inc. (2015). Table of contents. In Wohlers report 2015. Wohlers. [Online; accessed 20-October-2015].
[Wright, 2014] Wright, R. (2014). Regulatory concerns hold back 3d printing on safety. [Online; accessed 17-October-2015].