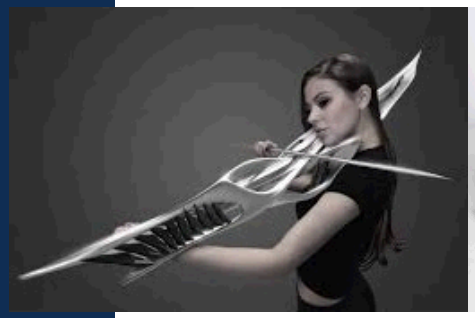
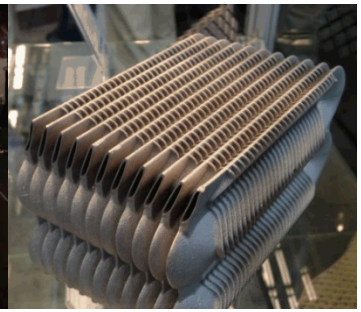
SAND2016-8027PE

Additive Manufacturing: A Changing Paradigm

Bradley Jared, PhD

Materials Science & Engineering Center



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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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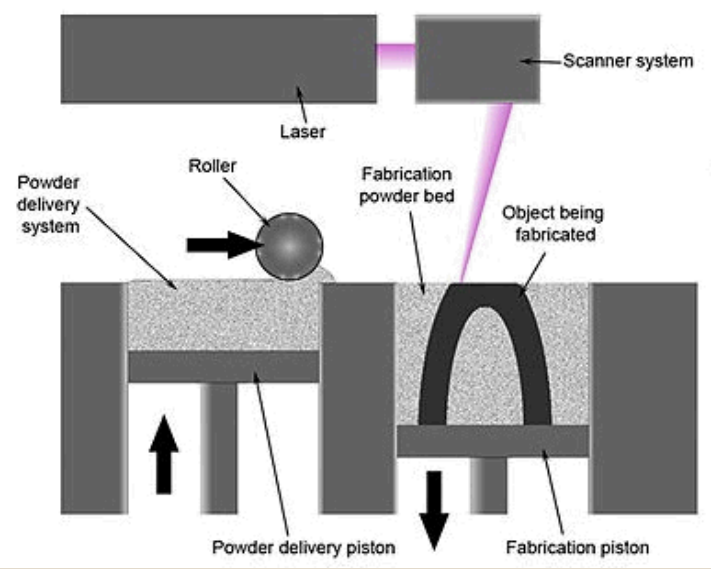
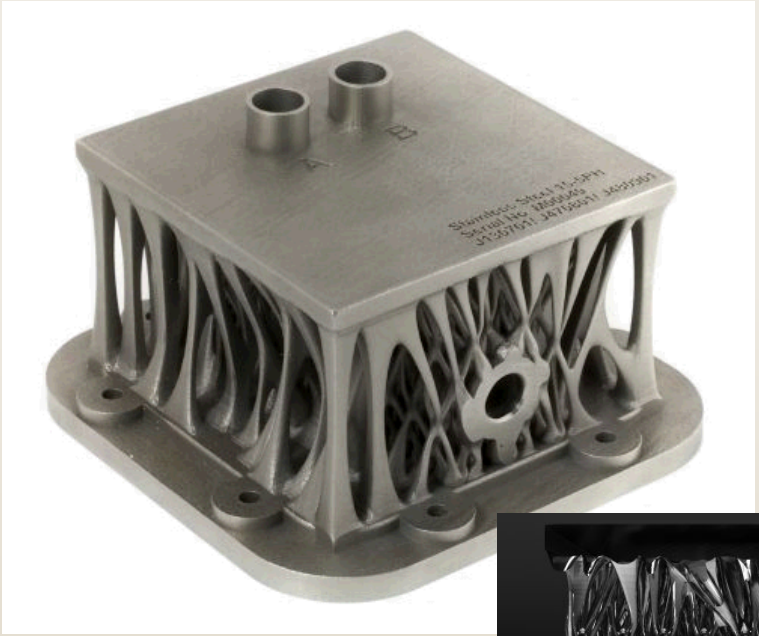
What is Additive Manufacturing?

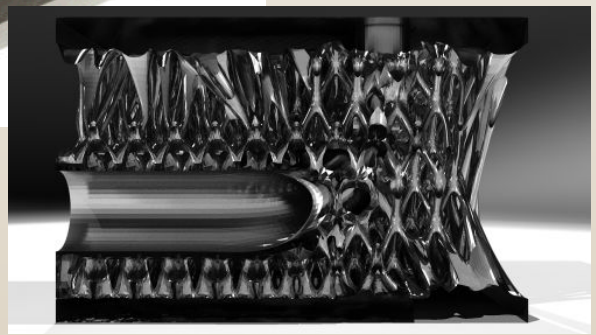
- ASTM F2792: A process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies.



from Wikipedia, "Selective laser sintering"



Within Technologies



Math You Need for AM

Name	Integral equations	Differential equations
Gauss's law	$\oiint_{\partial\Omega} \mathbf{E}\cdot\mathrm{d}\mathbf{S} = \frac{1}{\varepsilon_0}\iiint_{\Omega}\rho\,\mathrm{d}V$	$\nabla\cdot\mathbf{E} = \frac{\rho}{\varepsilon_0}$
Gauss's law for magnetism	$\oiint_{\partial\Omega} \mathbf{B}\cdot\mathrm{d}\mathbf{S} = 0$	$\nabla\cdot\mathbf{B} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\oint_{\partial\Sigma} \mathbf{E}\cdot\mathrm{d}\boldsymbol{\ell} = -\frac{\mathrm{d}}{\mathrm{d}t}\iint_{\Sigma}\mathbf{B}\cdot\mathrm{d}\mathbf{S}$	$\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t}$
Ampère's circuital law (with Maxwell's addition)	$\oint_{\partial\Sigma} \mathbf{B}\cdot\mathrm{d}\boldsymbol{\ell} = \mu_0\iint_{\Sigma}\mathbf{J}\cdot\mathrm{d}\mathbf{S} + \mu_0\varepsilon_0\frac{\mathrm{d}}{\mathrm{d}t}\iint_{\Sigma}\mathbf{E}\cdot\mathrm{d}\mathbf{S}$	$\nabla\times\mathbf{B} = \mu_0\left(\mathbf{J} + \varepsilon_0\frac{\partial\mathbf{E}}{\partial t}\right)$

Maxwell's Equations (electromagnetics)

$$\frac{v^2}{2} + gz + \frac{p}{\rho} = C$$

Bernoulli's Equation (fluid dynamics)

$$\boldsymbol{F} = m\frac{d\boldsymbol{v}}{dt} = m\boldsymbol{a}$$

Newton's Second Law (dynamics)

Schrödinger equation *(general)*

$$i\hbar\frac{d}{dt}|\psi(t)\rangle = H|\psi(t)\rangle$$

Heisenberg picture *(general)*

$$\frac{d}{dt}A(t) = \frac{i}{\hbar}[H, A(t)] + \frac{\partial A(t)}{\partial t},$$

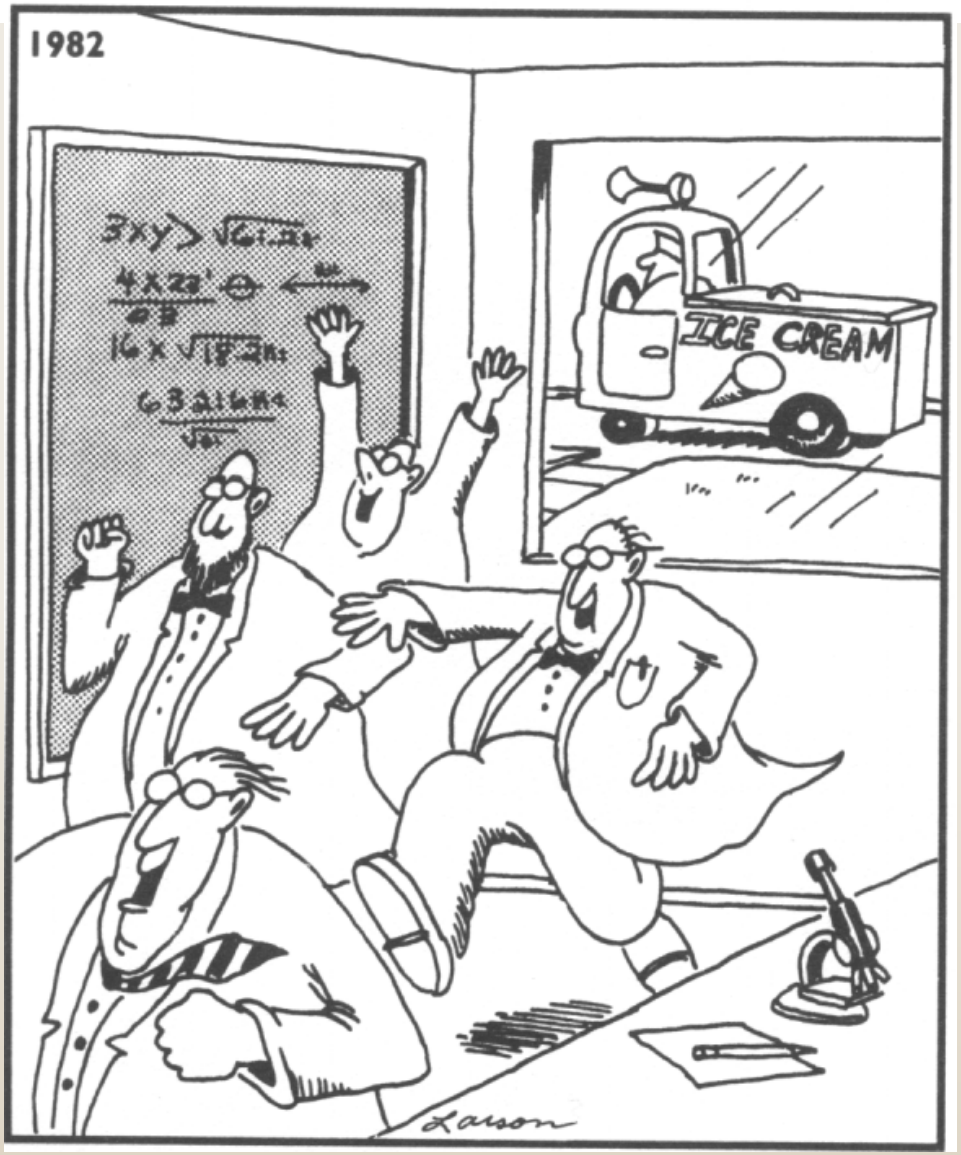
Quantum mechanics

$$\frac{\mathrm{d}^2}{\mathrm{d}x^2}\left(EI\frac{\mathrm{d}\varphi}{\mathrm{d}x}\right) = q(x,t)$$

$$\frac{\mathrm{d}w}{\mathrm{d}x} = \varphi - \frac{1}{\kappa AG}\frac{\mathrm{d}}{\mathrm{d}x}\left(EI\frac{\mathrm{d}\varphi}{\mathrm{d}x}\right)$$

Quasi-static Timoshenko Beam Theory (solid mechanics)

Math You Need for AM



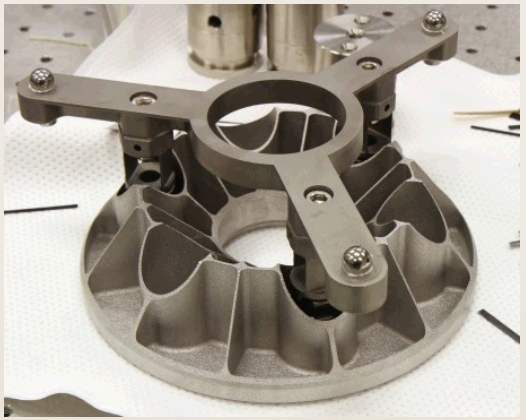
Far Side, Gary Larson, 1982

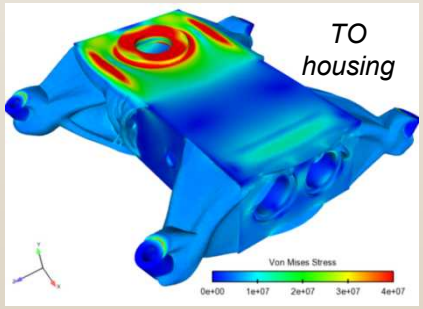
Why Additive?

- Reduce risk, accelerate development
  - simplify assembly, material use & processing
  - prototypes, test hardware, tooling & fixturing
    - cost reductions often 2-10x
- Add value
  - design & optimize for performance, not mfg
    - complex freeforms, internal structures, integration
  - engineered materials
    - gradient compositions
    - microstructure optimization & control
    - multi-material integration

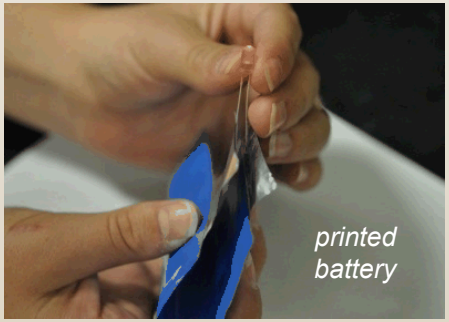
Sandia Hand, 50% built w/AM, cost ~$10k

prototype Al AM mirror & structure

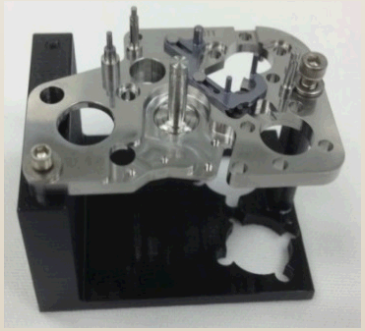




TO housing



printed battery



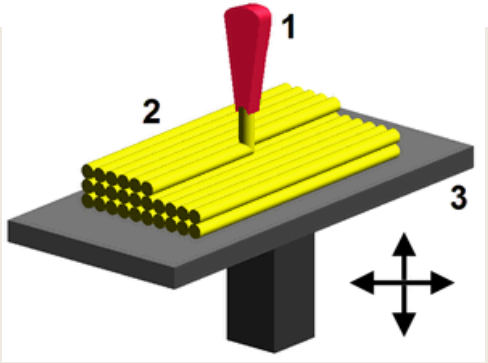
fixture generated in 1 day

6 Weeks, 6 Engineers And…

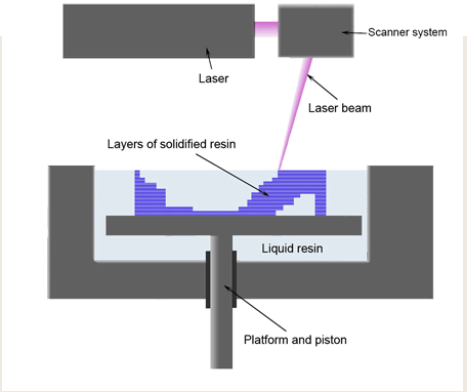
Oak Ridge National Lab/Cincinnati Inc.
50th Anniversary "BAAM" Shelby Cobra

ASTM “Process Categories”

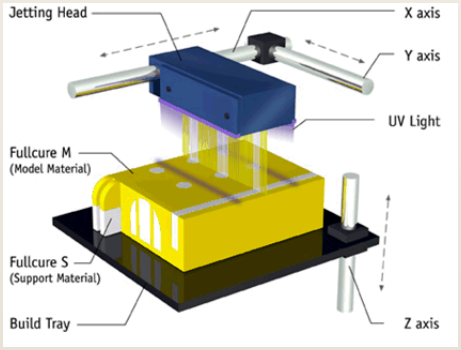
- Material extrusion
  - fused deposition modeling
  - direct write
  - viscous inks, thermoplastics
- Vat photopolymerization
  - stereolithography
  - photopolymers, epoxies
- Material jetting
  - Objet
  - photopolymers
- Binder jet
  - ZCorp, ExOne
  - binder printed into powder, infused w/filler



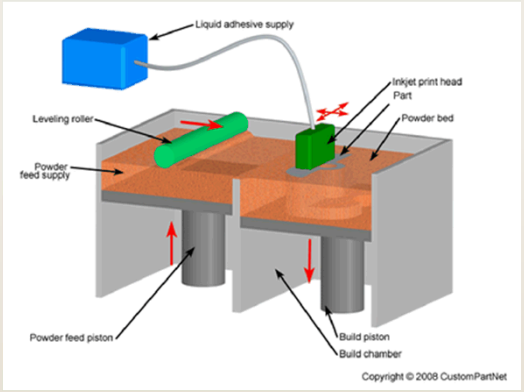
“Fused deposition modelling”, Wikipedia



“Stereolithography”, Wikipedia



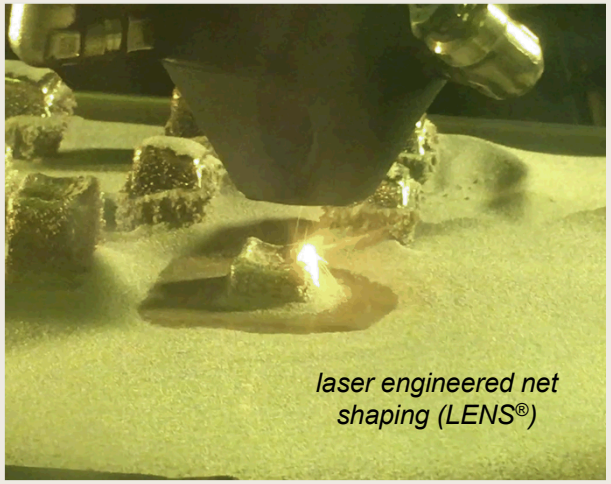
Objet Polyjet, www.me.vt.edu



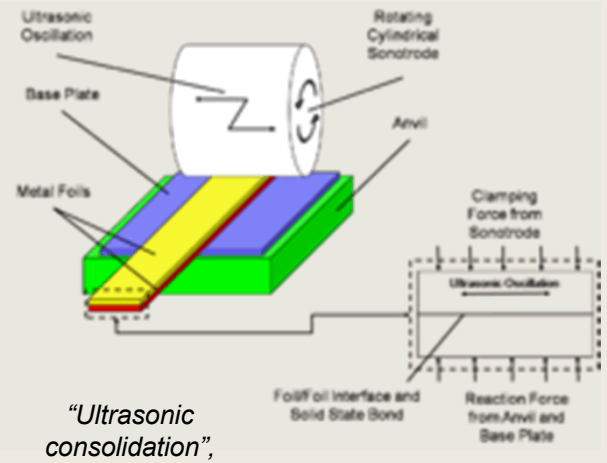
Binder jetting, www.utwente.nl

ASTM "Process Categories"

- Directed energy deposition
  - metals, ceramics
- Powder bed fusion
  - laser based
    - thermoplastics, metals, ceramics
  - electron beam melting
    - metals
- Sheet lamination
  - Fabrisonic (ultrasonics)
  - Mcor (paper)
  - multi-material composites

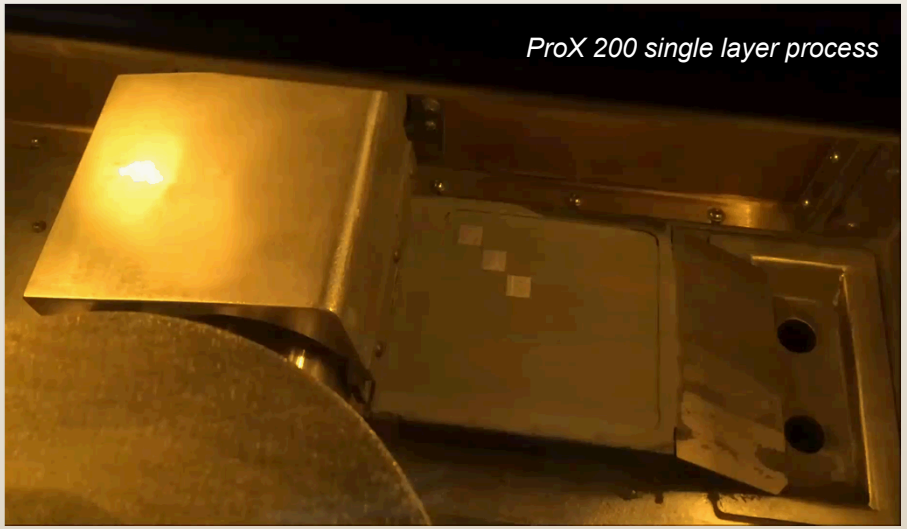


laser engineered net shaping (LENS®)



"Ultrasonic consolidation", Wikipedia

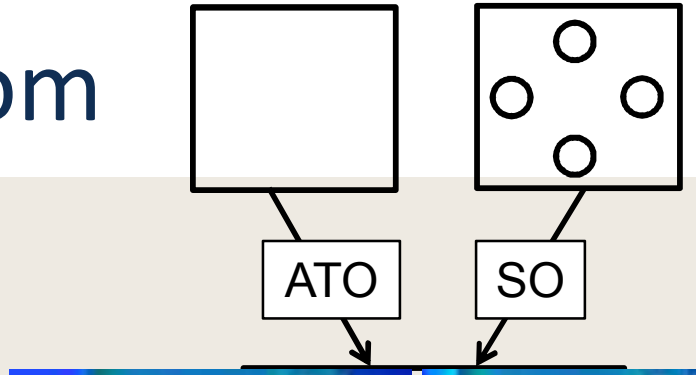
GE LEAP engine fuel nozzle

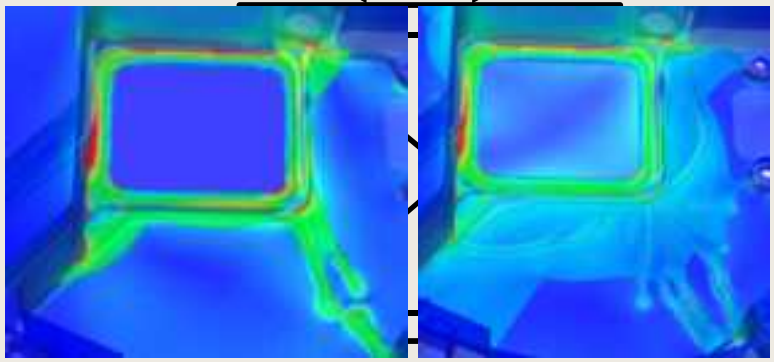


ProX 200 single layer process

New Design Freedom

- Computational synthesis for optimal material use
  - topological (TO) & shape optimizations (SO)
  - leverages “complexity is preferred”
  - bio-mimicry requires AM
- Changes
  - who holds IP?
  - roles & skills sets (i.e. maker)
  - increased systems emphasis

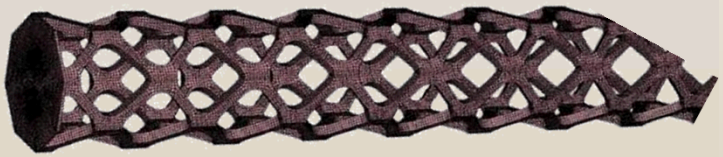




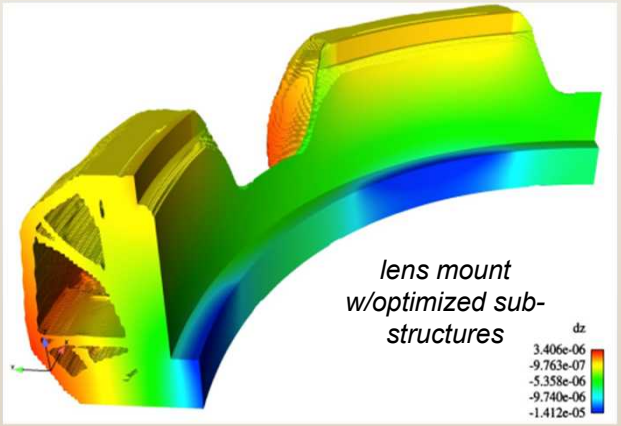
+ 0.55% volume
- 52% deflection

+ 3.3% volume
- 64% deflection

elasto-static stiffness optimization

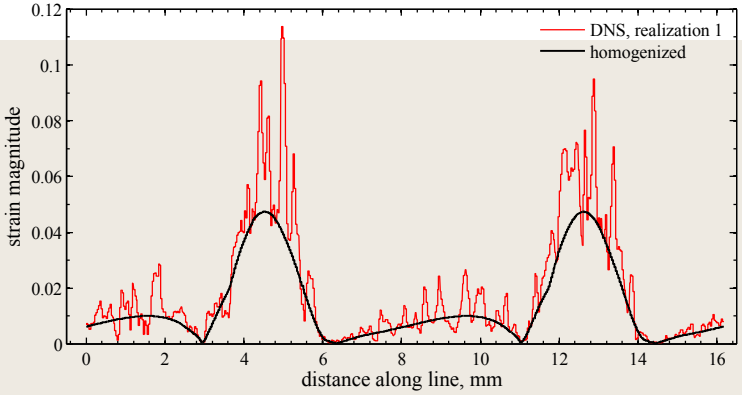


solution for a bar in pure torsion resembles a cholla cactus

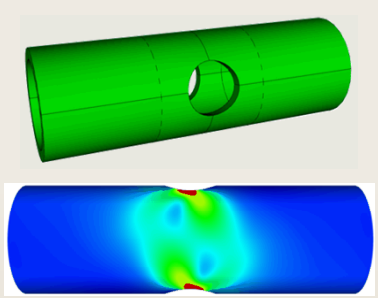


Engineered Materials

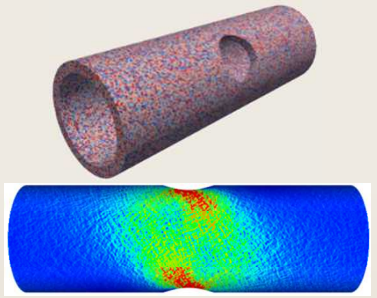
- Integrated Computational Materials Engineering (ICME)
  - materials analog to mechanical engineering
- Voxel access introduces new opportunities for control & design
- IP
  - similar to chemistry formulations?
  - specification?



strain field due to tension-torsion

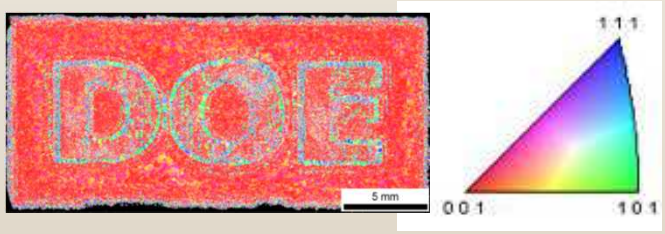


continuum model

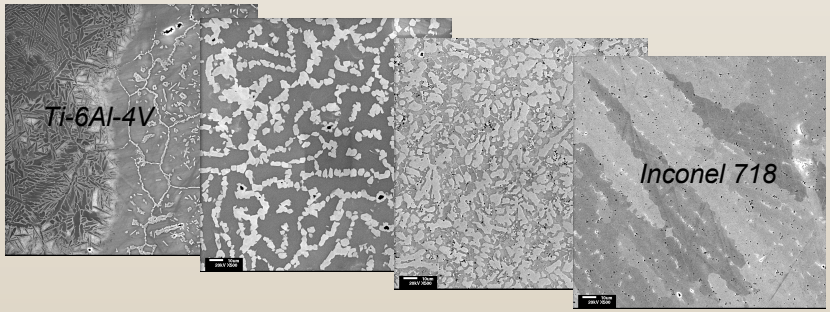


crystal plasticity model

AM Inconel 718 texture control demo by ORNL



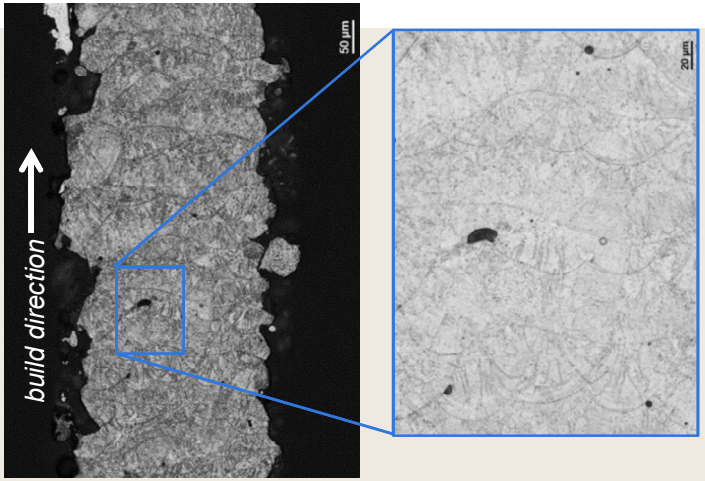
"We can now control local material properties, which will change the future of how we engineer metallic components," R. Dehoff



LENS® functionally graded materials

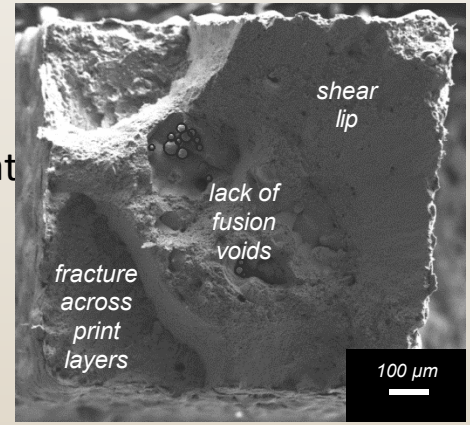
Material Challenges

- Material formation concurrent w/geometry
  - voxel access – control vs. defects
  - how to ID a bad part?
    - complexity isn't "free"
    - engineered materials are easier to fabricate than validate

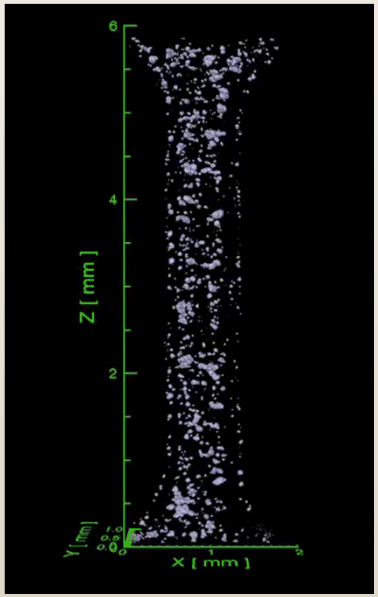


defects in 17-4 PH w/ 0.015" nominal wall thickness

- Processes
  - currently open loop
    - only accommodates large material margins
  - new paradigm required for qualification / certification
  - primary barrier for high consequence applicat



17-4PH dogbone fracture surface



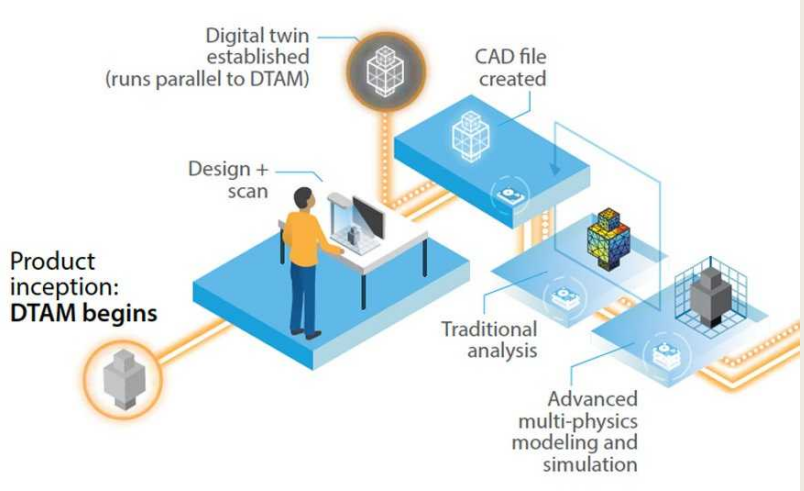
17-4PH dogbone porosity

- Liability
  - equipment vendor, user, engineer, ?

Complexity is More Accessible

- Counterfeiting / piracy
  - “brute force” reverse engineering
    - ex. 3D scanning
  - cyber espionage
  - requires identification / authorization
  - leverages access to the digital thread
    - analog to music & literature
    - copyright vs. patent?
  - IP for emergency repairs

- Safety
  - material assurance
  - new product paradigm
    - anyone can be a designer & manufacturer



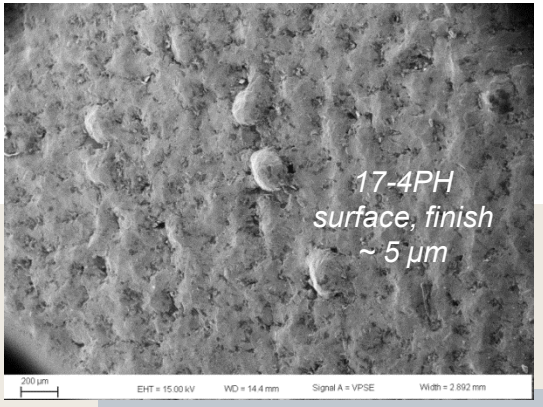
Digital thread concept, Deloitte University Press

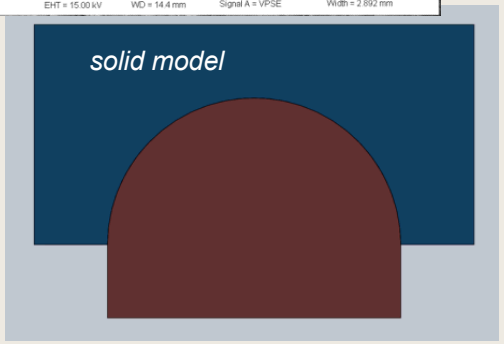
1911 .45 semi-automatic pistol fresh off the 3D printer, 2013, Stratasys Direct Manufacturing

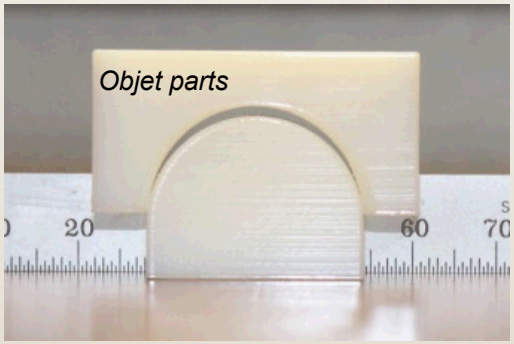
http://blogs.computerworld.com/emerging-technologies/23303/need-last-minute-christmas-gift-howabout-12000-3d-printed-gun

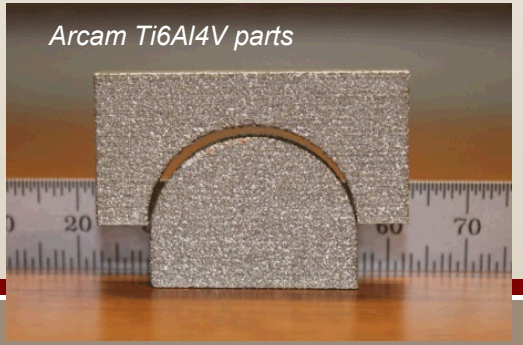
Why *Not* AM

- Manufacturing constraints exist
  - support structures, powder removal, overhangs
  - size, accuracy, finish
    - residual stress, distortion
  - material selection
  - post processing (hidden costs)
    - heat treat, HIP, powder / support removal, finish machining…
  - throughput
    - not always quicker or cheaper
- Materials
  - metal
    - “competition” is casting, not machining
  - polymer
    - greatest maturity & flexibility
    - limited engineering plastics available
  - ceramics
    - lowest maturity & availability
- Dynamic industry, improvements will continue…





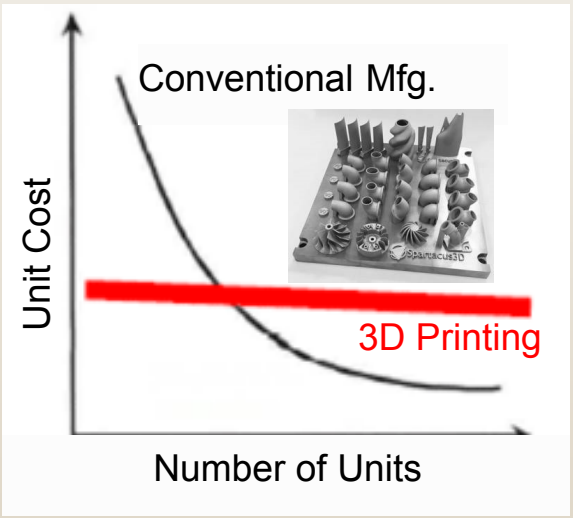


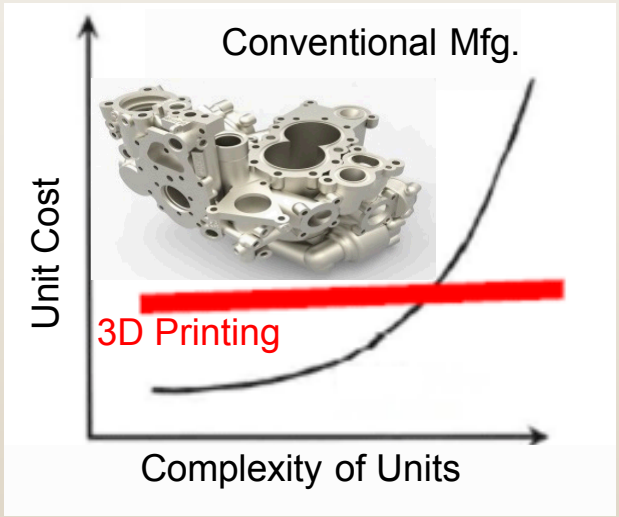


Where is AM Headed?

- Will supplement & complement (not supplant) most traditional mfg cycles
  - clear for short term, unclear for long times
  - industries w/high price, low throughput, customization at risk
- Mass customization is a game changer
  - already seen in dentistry, art, fashion
  - product on demand

AMMONITE, Fernando Romero





notional cost vs. volume & cost vs. complexity

3D Systems 3DMe

http://ideasdesign.today/lifestyle/3d-printed-heels-by-famous-architects

QUESTIONS?

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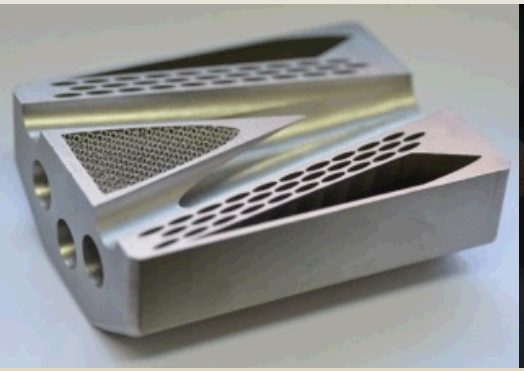
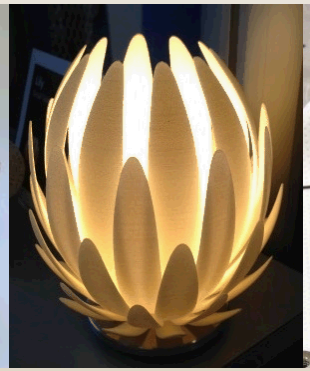
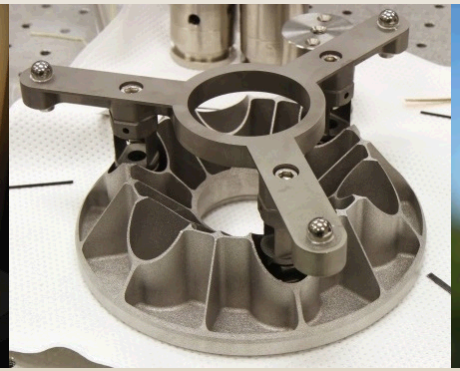
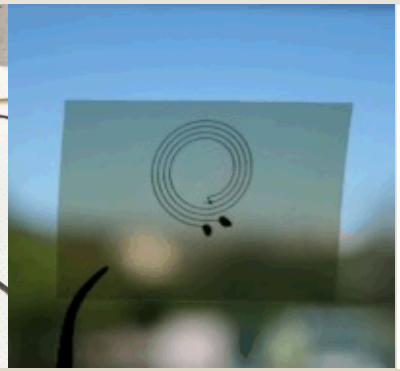
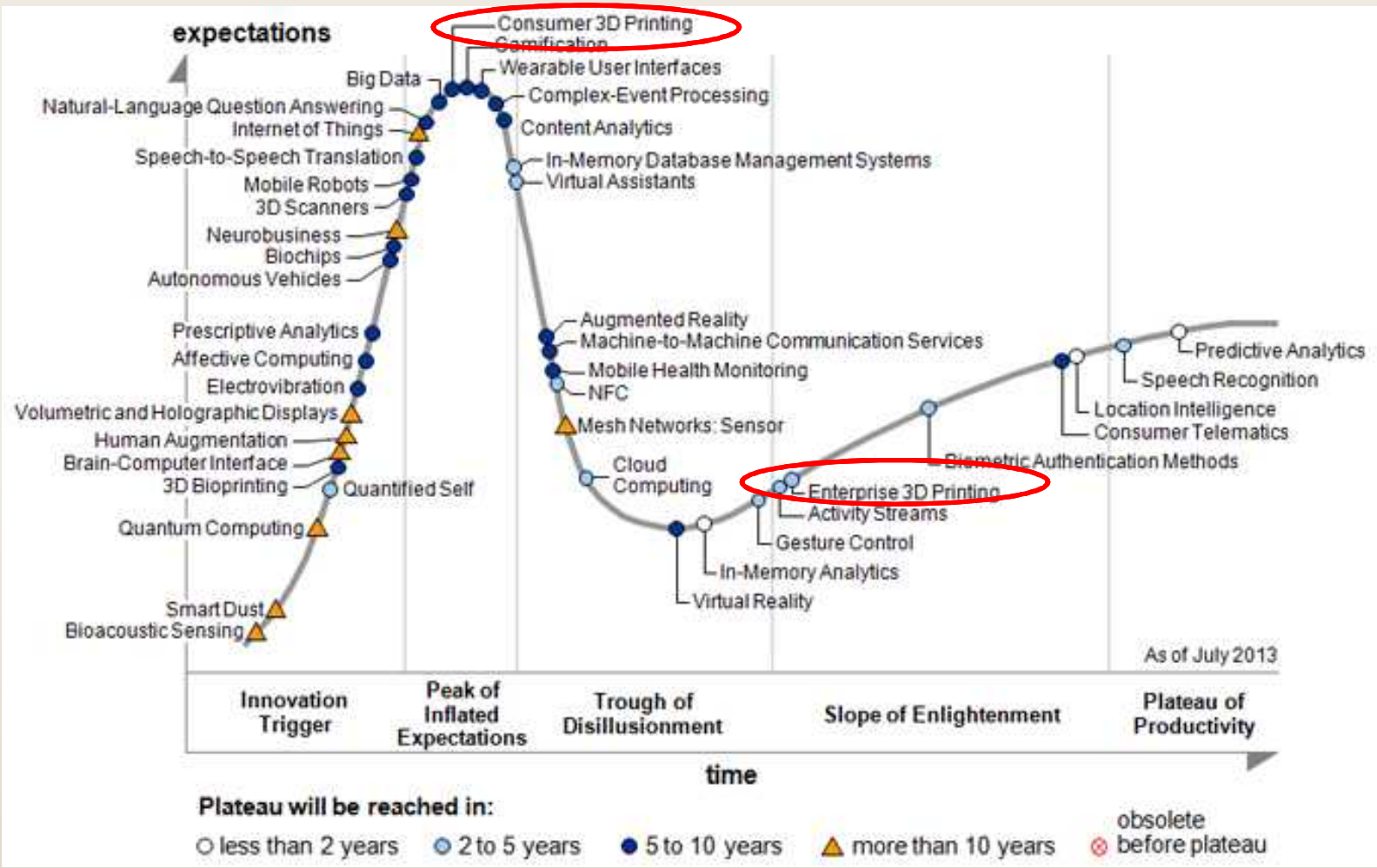






Gartner's 2013 Hype Cycle



- Neither a distraction on a panacea…

http://www.gartner.com/newsroom/id/2575515