Additive Manufacturing – Module 6

Spring 2015

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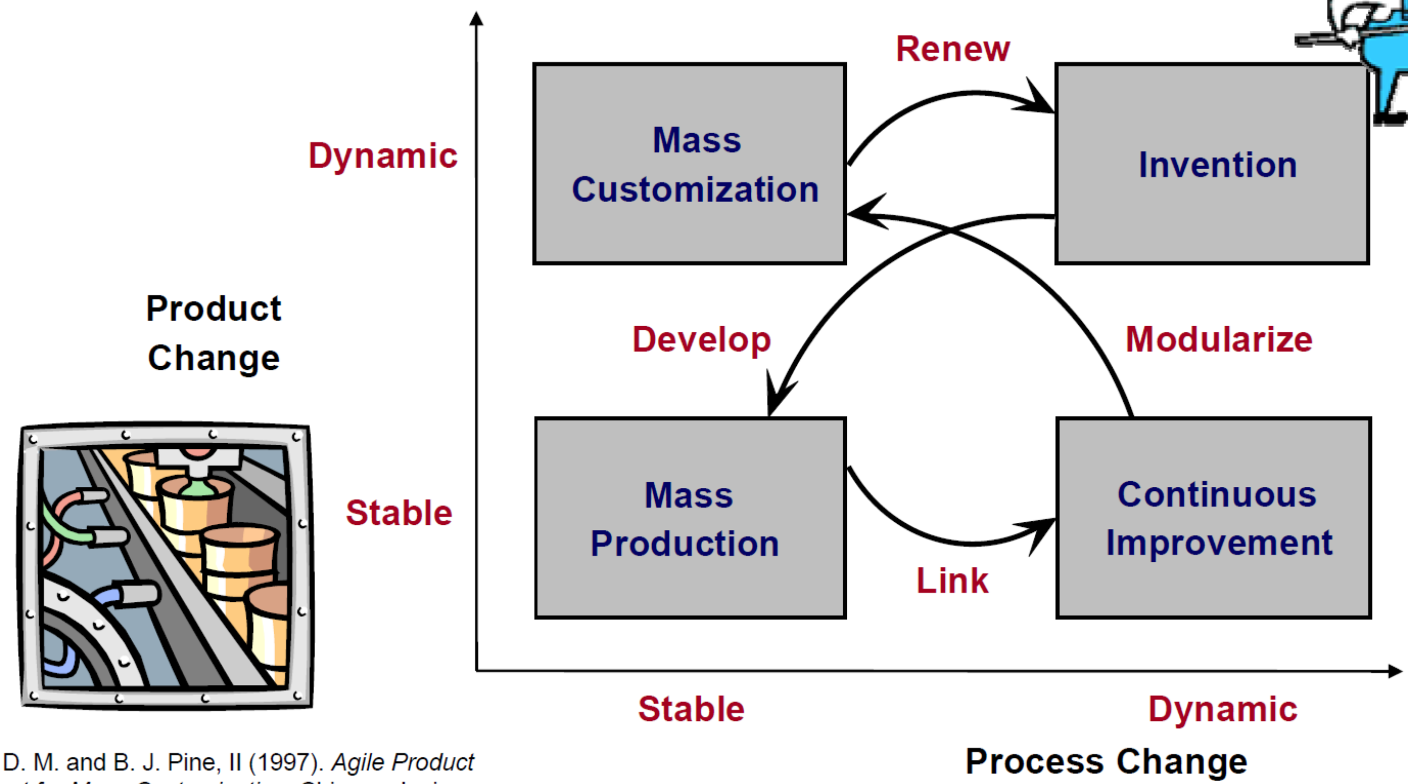
Design for AM

Manufacturing paradigms

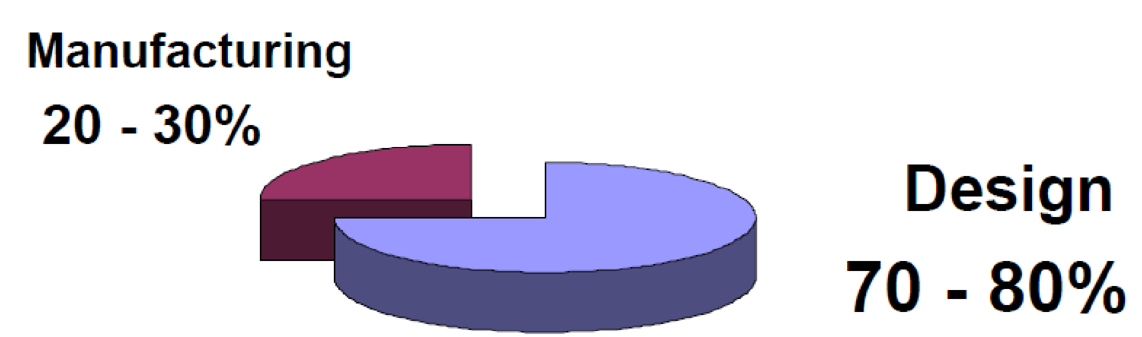


Anderson, D. M. and B. J. Pine, II (1997). *Agile Product Development for Mass Customization.* Chicago, Irwin.

Design for AM

Design
Optimization
Geometry
Materials

Design for Manufacturing



Concept Design

↓

Design for Assembly

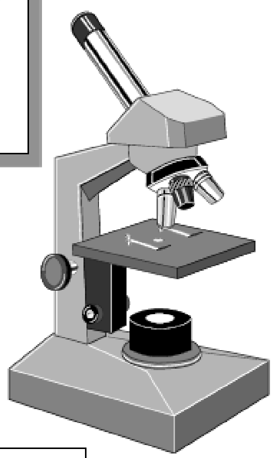
↓

Design for Manufacturing

↓

Detailed Design

Optimize Design for Part Count and Assembly



Optimize Design for Production Readiness

Source: David Stienstra@Rose-Hulman

Design for AM

Design for Assembly (DFA) Principles

- Minimize part **count**
- Design parts with **self-locating features**
- Design parts with **self-fastening features**
- Minimize **reorientation** of parts during assembly
- Design parts for **retrieval, handling, & insertion**
- Emphasize '**Top-Down**' assemblies
- **Standardize** parts…minimum use of fasteners.
- Encourage **modular** design
- Design for a **base** part to locate other components
- Design for component **symmetry** for insertion

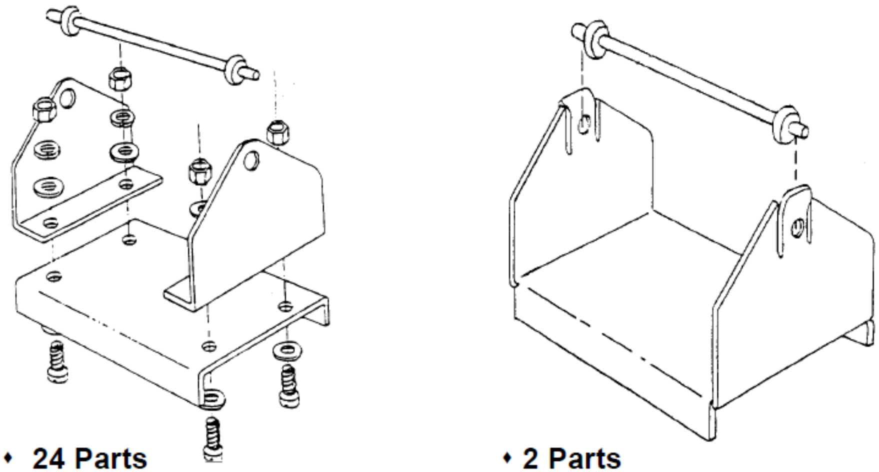
- Minimize DFA complexity: $\sqrt{\sum N_p \cdot \sum N_i}$
  - N_p: number of parts
  - N_i: number of part to part interfaces

Source: David Stienstra@Rose-Hulman

Design for AM

Design
Optimization
Geometry
Materials

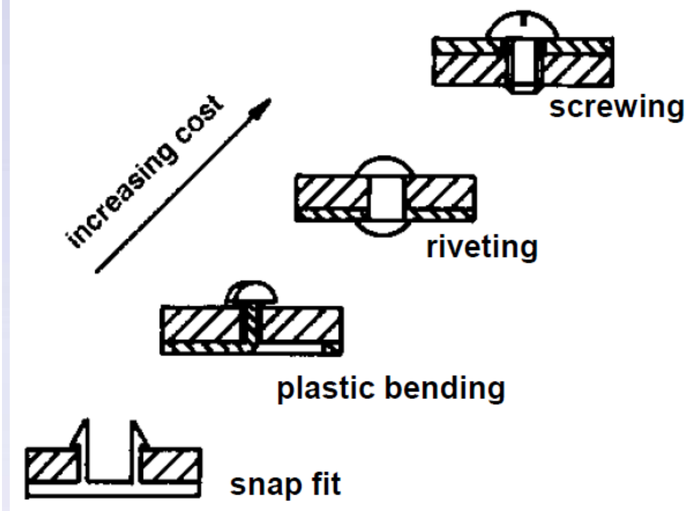
Design for Assembly Principles



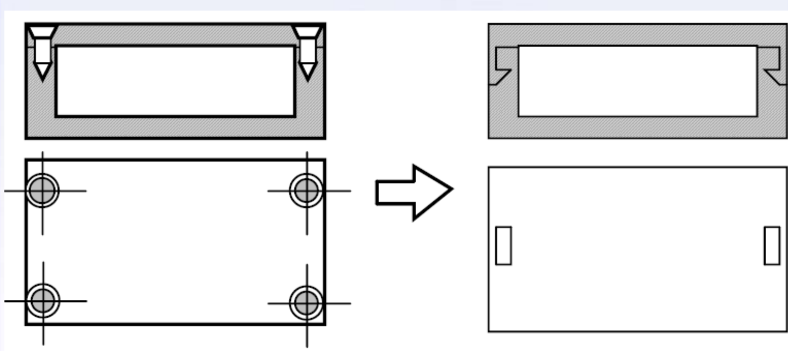
- 24 Parts
- 8 different parts
- multiple mfg. & assembly processes necessary

- 2 Parts
- 2 Manufacturing processes
- one assembly step

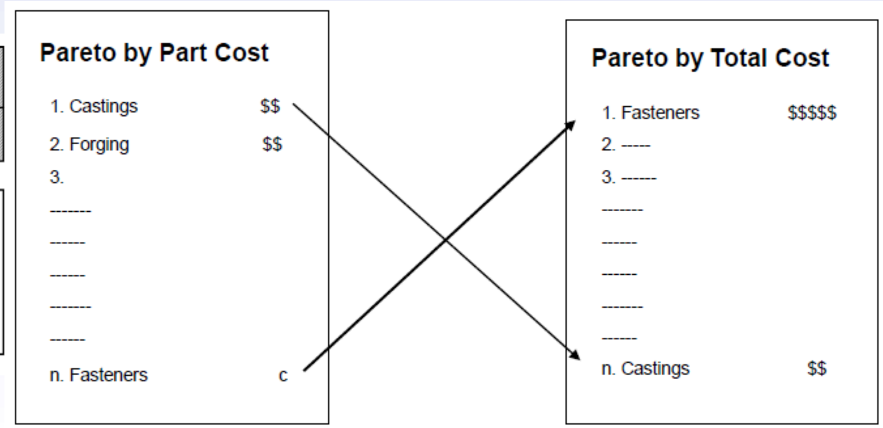
Component elimination



Fastener cost



Self-fastening feature

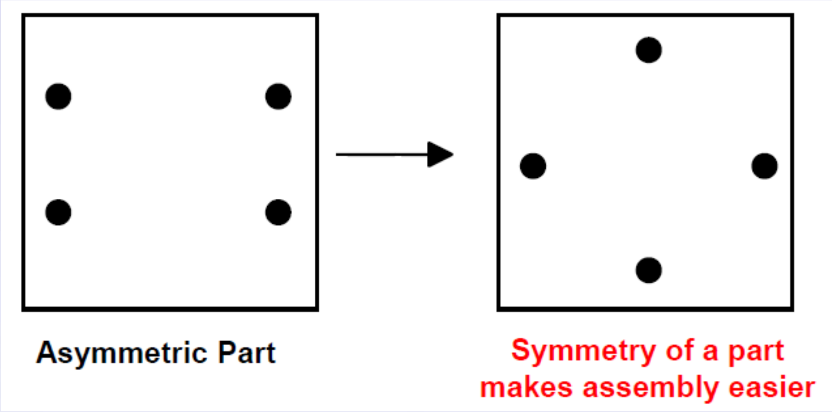


Cost of fastening

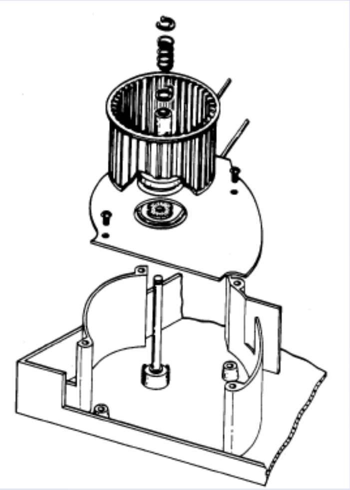
Source: David Stienstra@Rose-Hulman

Design for AM

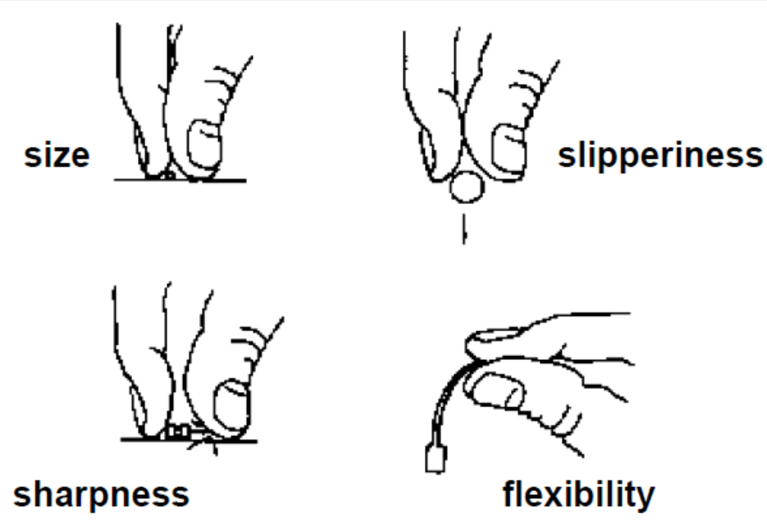
Design for Assembly Principles



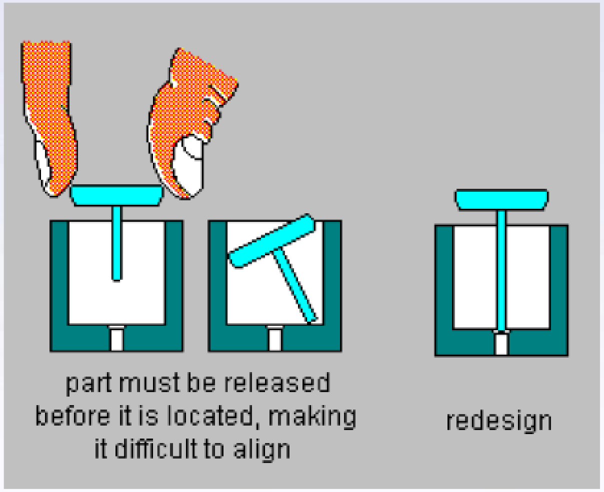
Symmetry eliminates reorientation



Top-down assembly



Handling difficulty



Self-locating

Source: David Stienstra@Rose-Hulman

Design for AM

Manufacturing processes

Machining	Casting	Bulk Def	Sheetmetal	Polymer	Assembly
Turning	Sand	Forging	Blanking	Extrusion	Welding
Facing	Shell Mold	Rolling	Punching	Injection Molding	Brazing
Boring	Plast. Mold	Wire Drawing	Bending	Compression Molding	Soldering
Planning	Ceram. Mold	Tube Drawing	Drawing	Blow Molding	Resistance Welding
Milling	Die	Extrusion	Deep Drawing	Transfer Molding	Adhesive Bonding
Drilling	Perm. Mold	Colming	Ironing	Coating	Press/snap fit
Grinding	Centrifugal	Roll Forming	Spinning	Thermoforming	Man. Assy
Sawing	Investment		Stretching		Flex. Assy
EDM					
Wire EDM					
Chem. milling					
ECM					
Laser					

Source: Dixon and Poly

Shaping	Forming	RP	Treatment	Assembly
Casting	Forging	SLA	Harden	Welding
Sintering	Extruding	SLS	Heat Treatment	Brazing
Electrolytic Deposition	Bending	3D Printing	Sintering and burning	Soldering
	Shearing	LENS	Magnetizing	Resistance Welding
	Pressing	UC	Photochemical Reactions	Adhesive Bonding
			Lazing	Press/snap fit

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Design for AM

AM³ Lab
Advanced Manufacturing | Modeling | Materials

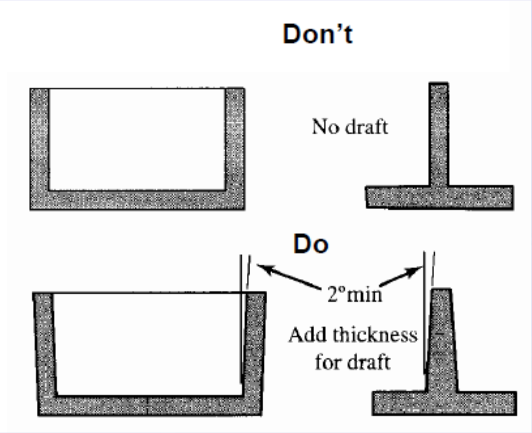
Design

Optimization

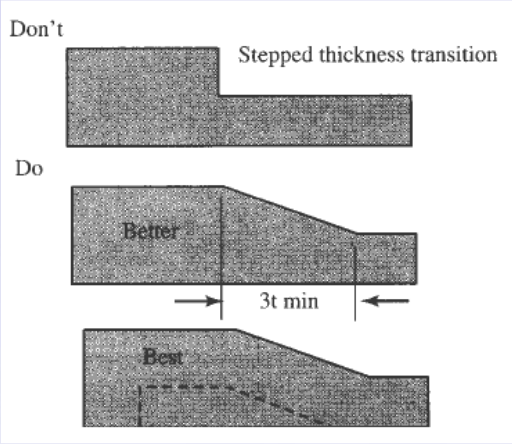
Geometry

Materials

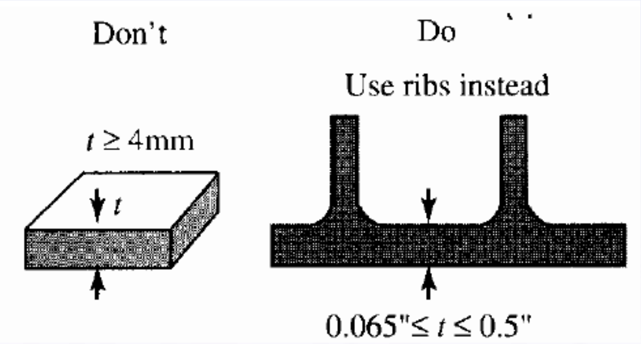
Design for Manufacturing (DFM) – injection molding



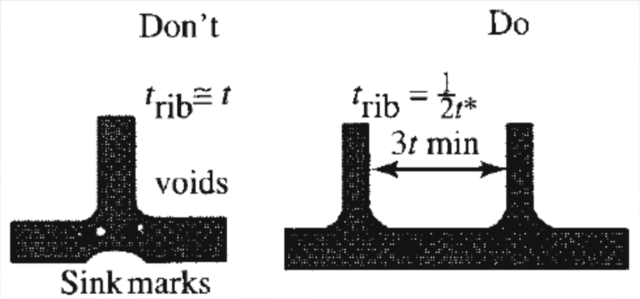
Provide adequate draft angle for easier part removal



Provide smooth transition, avoid changes in thickness when possible



Minimize section thickness; cooling time is proportional to the square of the thickness. Reduce cost by reducing the cooling time.

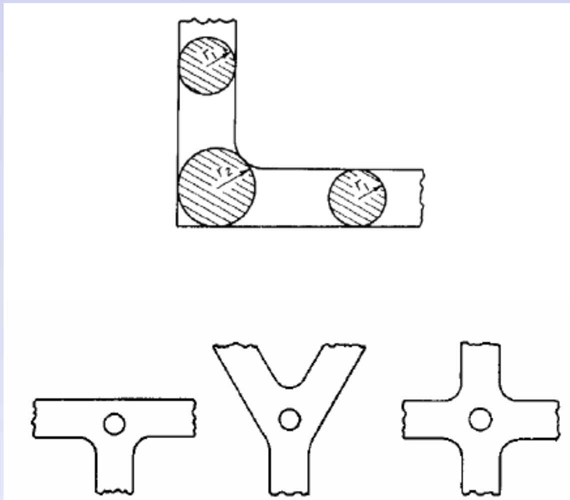


Keep rib thicknesses less than 60% of the part thickness in order to prevent voids and sinks.

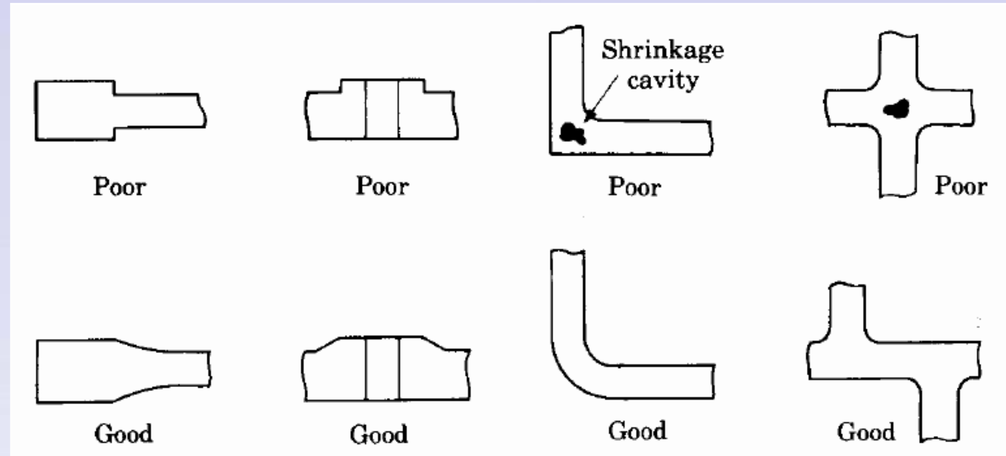
Credit: Dr. Georges M. Fadel@Clemson

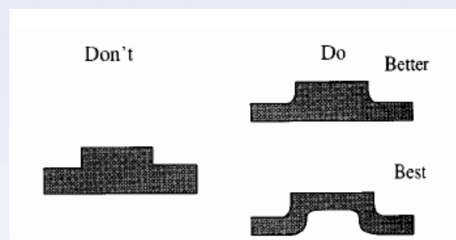
Design for AM

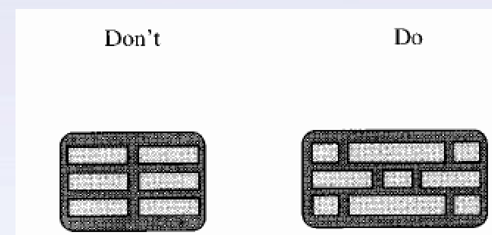
Design for Manufacturing (DFM) – Casting

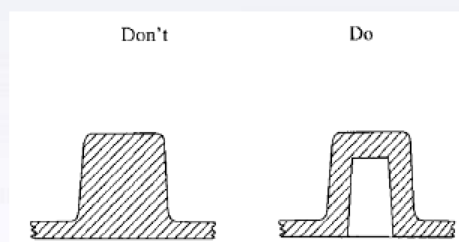


Hot spots –thick sections cool slower than other sections causing abnormal shrinkage. Defects such as voids, cracks and porosity are created.









Design for AM

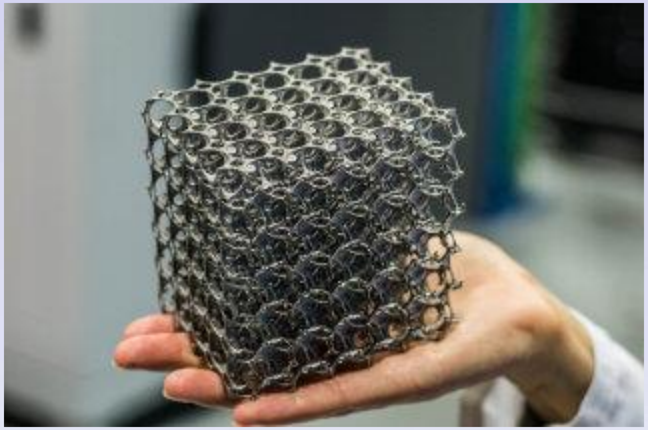
Design

Optimization

Geometry

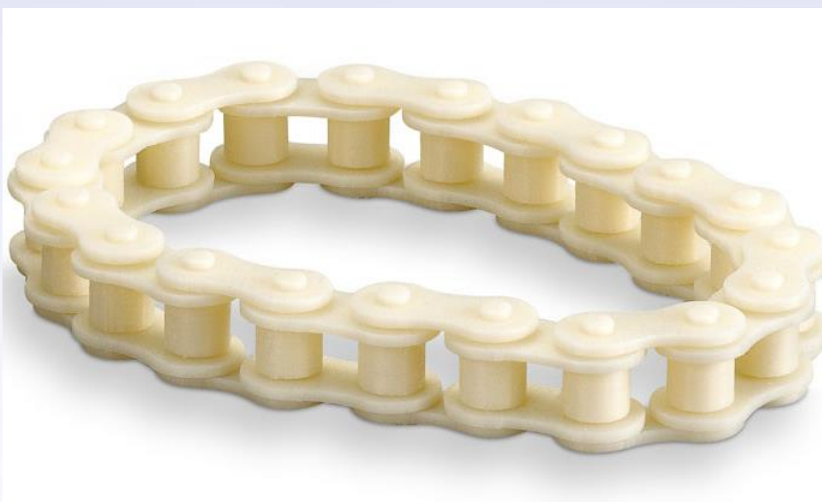
Materials

Design for Additive Manufacturing (DFAM)



Complex geometry

Multimaterial (Stratasys)



Assembly

Functionality (credit: UTEP)

- **Need next-generation CAD**
- **Need to find ways to use the overwhelming design freedom**

Design for AM

Design

Optimization

Geometry

Materials

Geometry Optimization

$$\text{Minimize} \quad f(\mathbf{x})$$

$$\textit{Subject to} \quad g(\mathbf{x}) \leq 0$$

$$h(\mathbf{x}) = 0$$

$f(\mathbf{x})$: Objective function to be minimized

$g(\mathbf{x})$: Inequality constraints

$h(\mathbf{x})$: Equality constraints

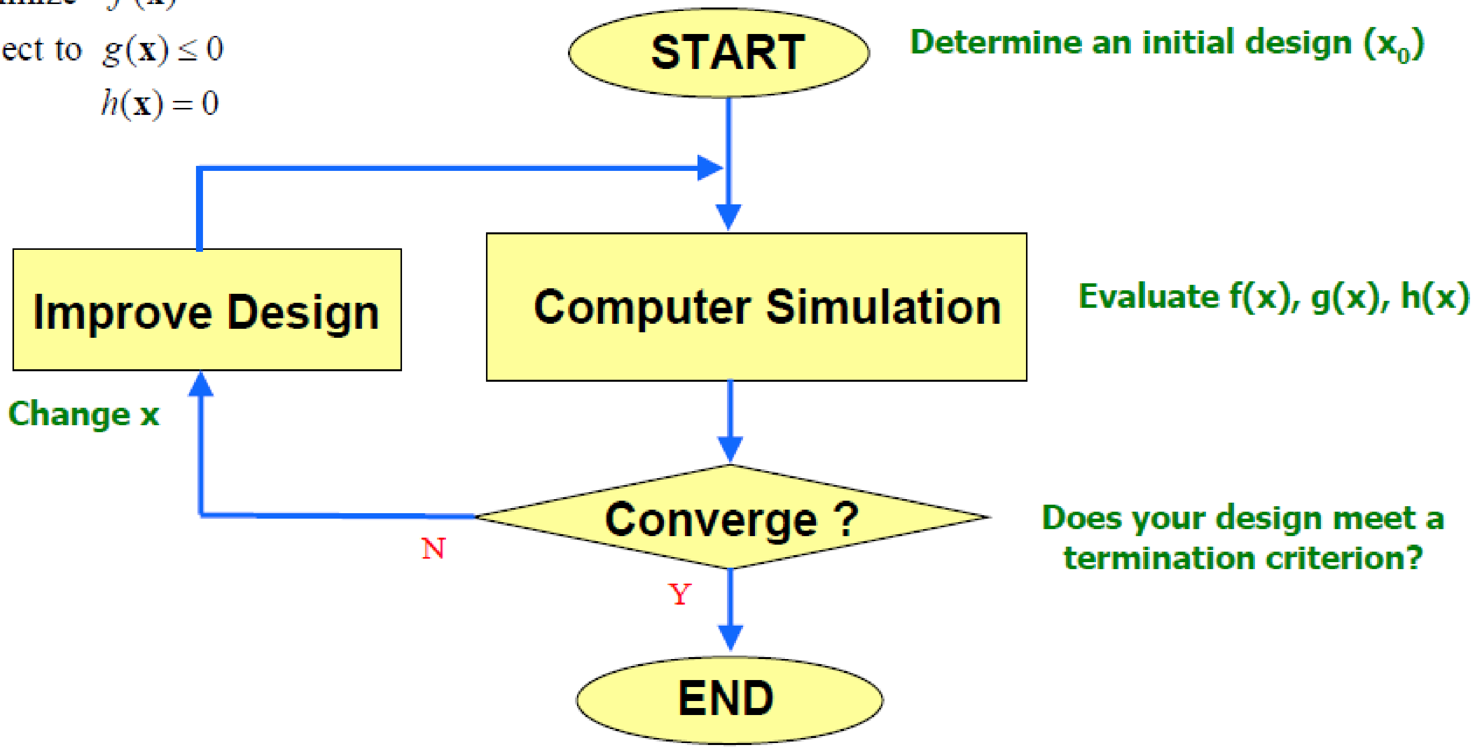
$\mathbf{x}$: Design variables

Source: Dr. Olivier de Weck@MIT

Design for AM

Geometry Optimization

$$\begin{aligned} &\text{Minimize} \quad f(\mathbf{x}) \\ &\text{Subject to} \quad g(\mathbf{x}) \le 0 \\ &\qquad\qquad\quad h(\mathbf{x}) = 0 \end{aligned}$$

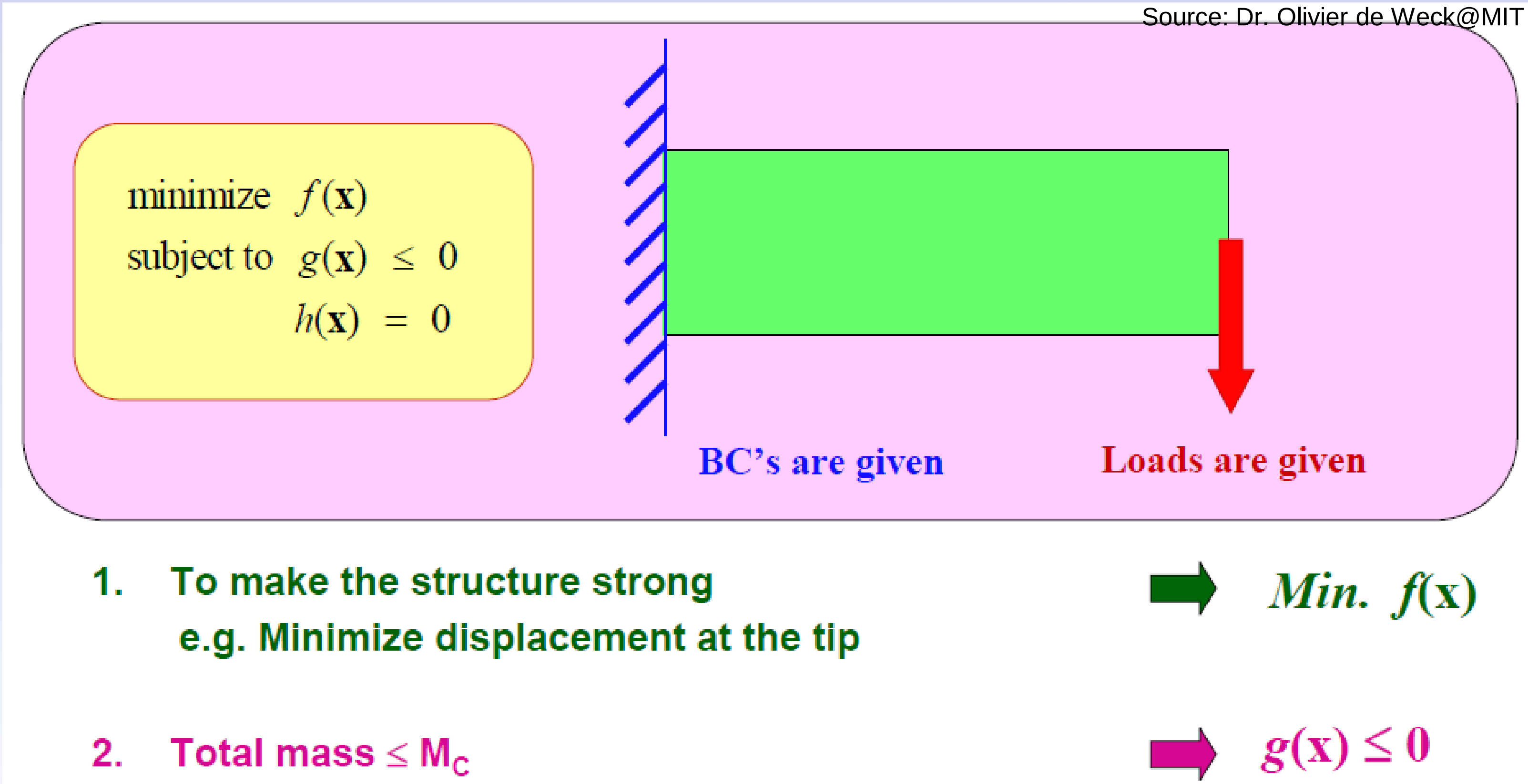


Optimization procedure

Source: Dr. Olivier de Weck@MIT

Design for AM

Geometry Optimization



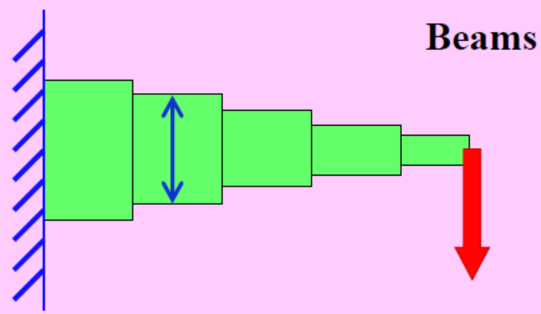
Structure optimization

Manufacturing perspective: One of the ultimate goal of the structure optimization is that standard deviation of the stress distribution becomes zero (each members in a structure has the stress of the same level).

Design for AM

Geometry Optimization

$$\begin{aligned} \text{minimize} \quad & f(\mathbf{x}) \\ \text{subject to} \quad & g(\mathbf{x}) \le 0 \\ & h(\mathbf{x}) = 0 \end{aligned}$$



Design variables (x)

x : thickness of each beam

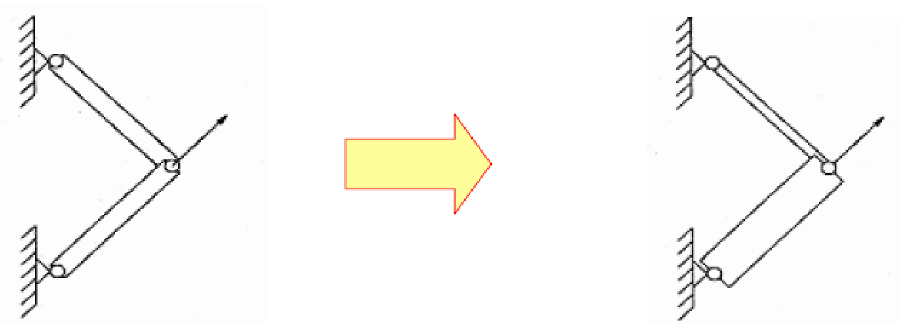
Number of design variables (ndv)

ndv = 5

f(x) : compliance

g(x) : mass

Size optimization



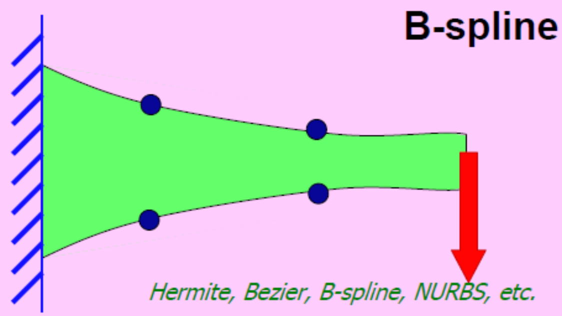
- Shape
  Topology } are given
- Optimize cross sections

Source: Dr. Olivier de Weck@MIT

Design for AM

Geometry Optimization

$$\begin{aligned} \text{minimize} \quad & f(\mathbf{x}) \\ \text{subject to} \quad & g(\mathbf{x}) \le 0 \\ & h(\mathbf{x}) = 0 \end{aligned}$$



Design variables (x)

x : control points of the B-spline

(position of each control point)

f(x) : compliance

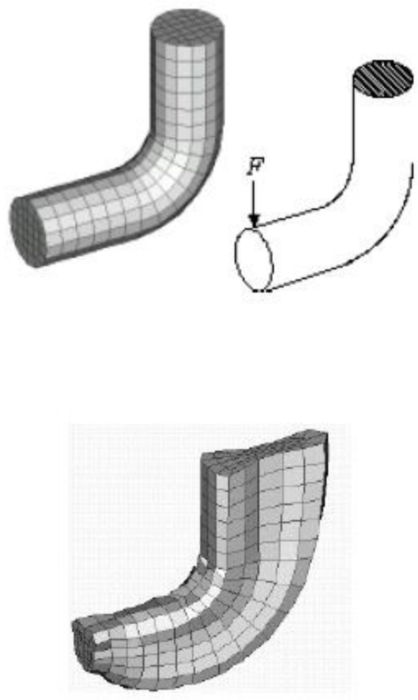
g(x) : mass

Number of design variables (ndv)

ndv = 8

Shape optimization

Hook problem

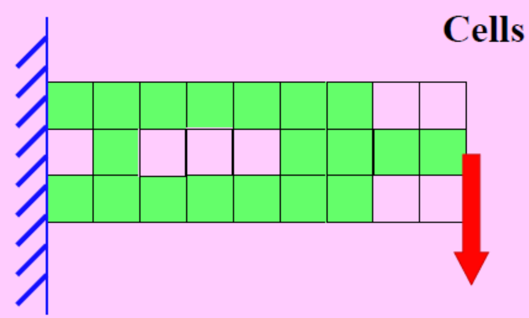


Source: Dr. Olivier de Weck@MIT

Design for AM

Geometry Optimization

$$\begin{aligned} \text{minimize} \quad & f(\mathbf{x}) \\ \text{subject to} \quad & g(\mathbf{x}) \leq 0 \\ & h(\mathbf{x}) = 0 \end{aligned}$$



Design variables (x)

x : density of each cell

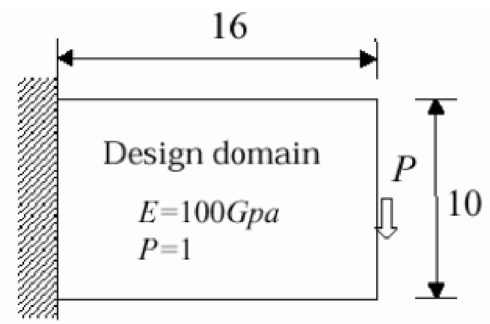
Number of design variables (ndv)

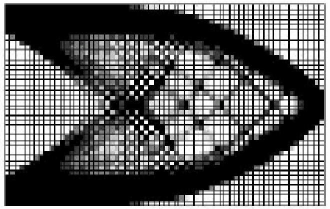
ndv = 27

f(x) : compliance

g(x) : mass

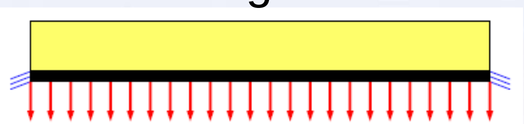
Short cantilever problem





Topology optimization (online tool: http://www.topopt.dtu.dk)

Bridge

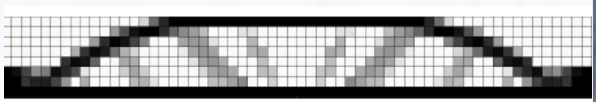


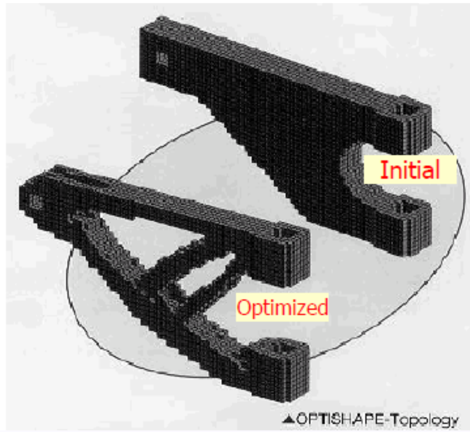
$$\text{Minimize} \quad \int_{\Gamma} F^t z^t d\Gamma,$$

$$\text{Subject to} \quad \int_{\Omega} \rho(x) d\Omega \leq M_o,$$

$$0 \leq \rho(x) \leq 1$$

Mass constraints: 35%



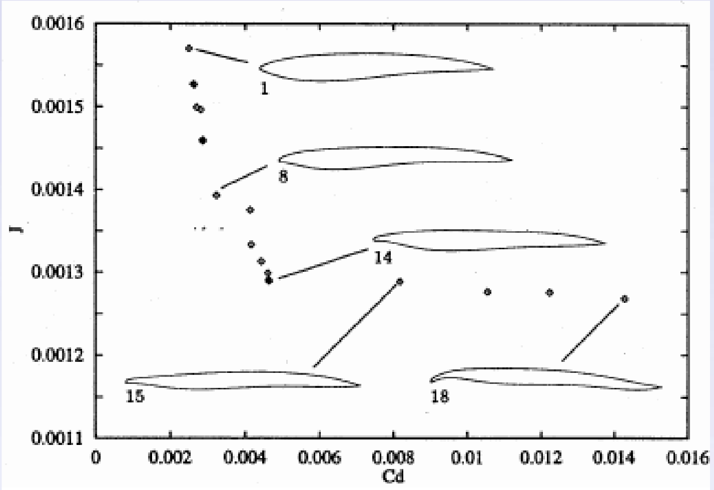


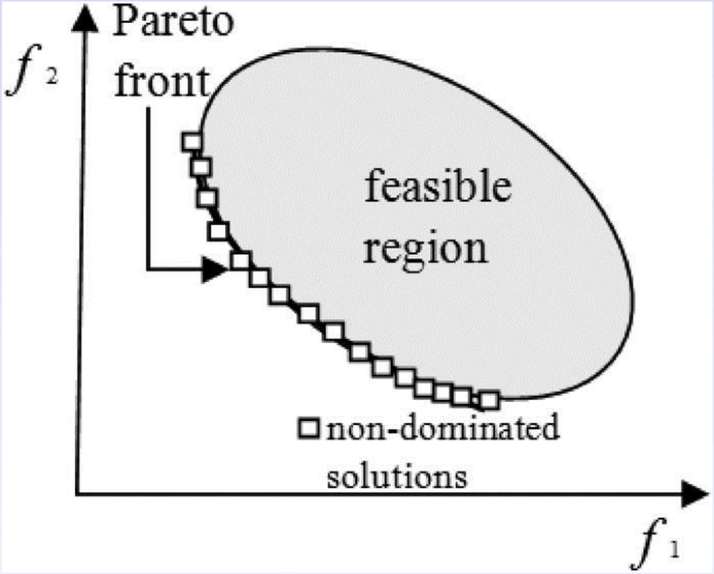
Source: Dr. Olivier de Weck@MIT

Design for AM

Geometry Optimization

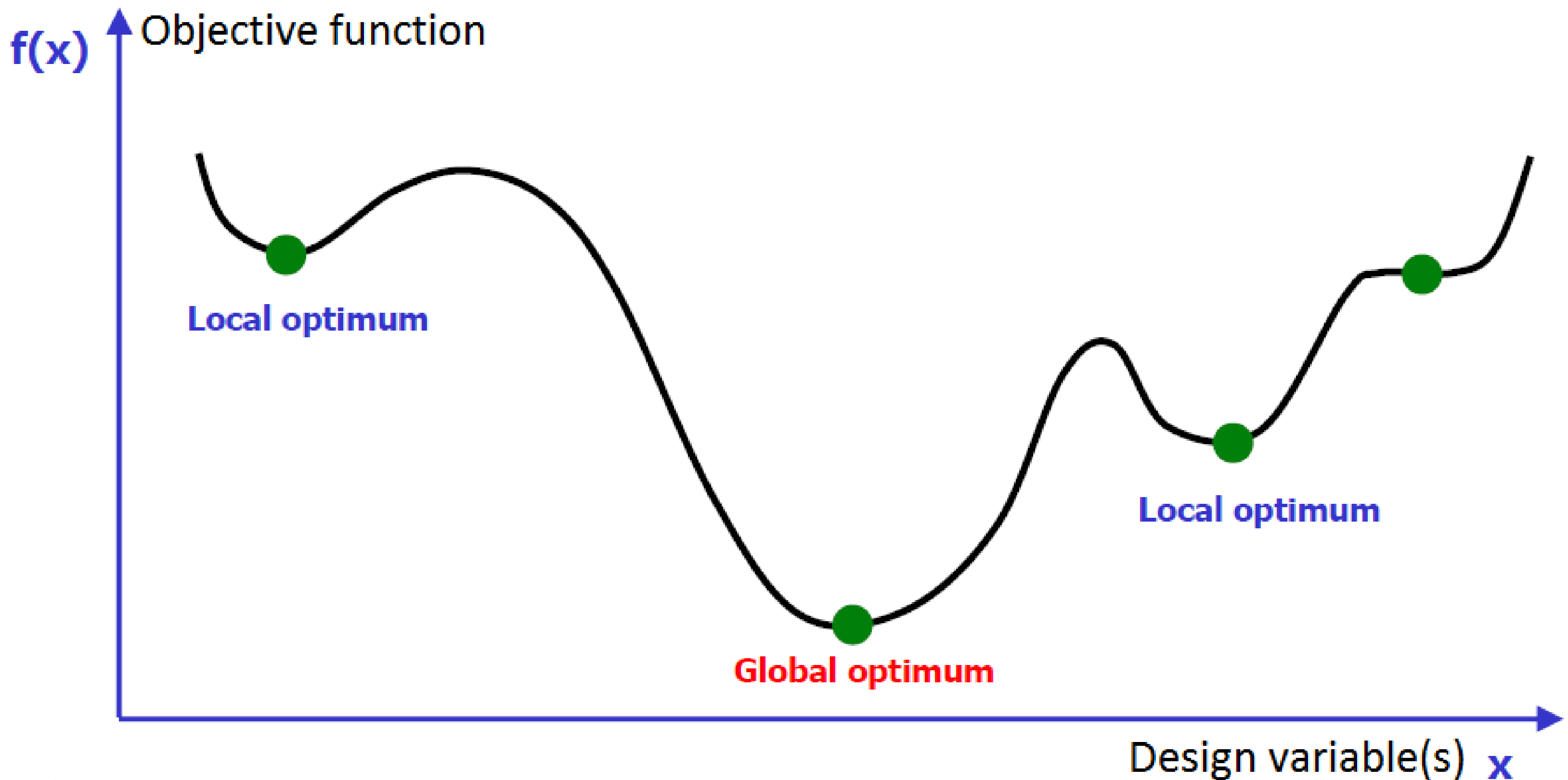
- **Multiobjective:**
  - **Drag coefficient**
  - **Amplitude of backscattered wave**

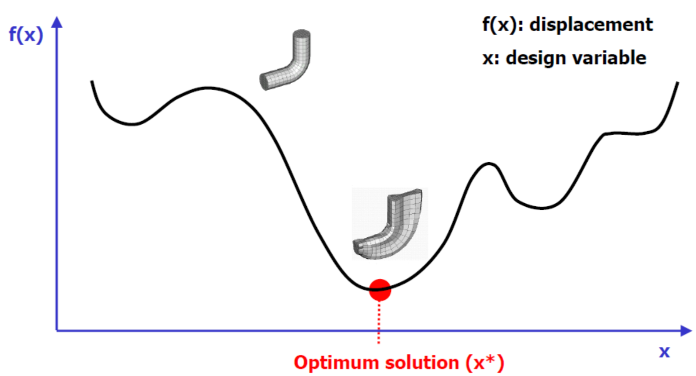




Pareto efficiency, or **Pareto optimality**, is a state of allocation of resources in which it is impossible to make any one individual better off without making at least one individual worse off. The term is named afterVilfredo Pareto (1848–1923), an Italian economist. (From Wikipedia)

Geometry Optimization

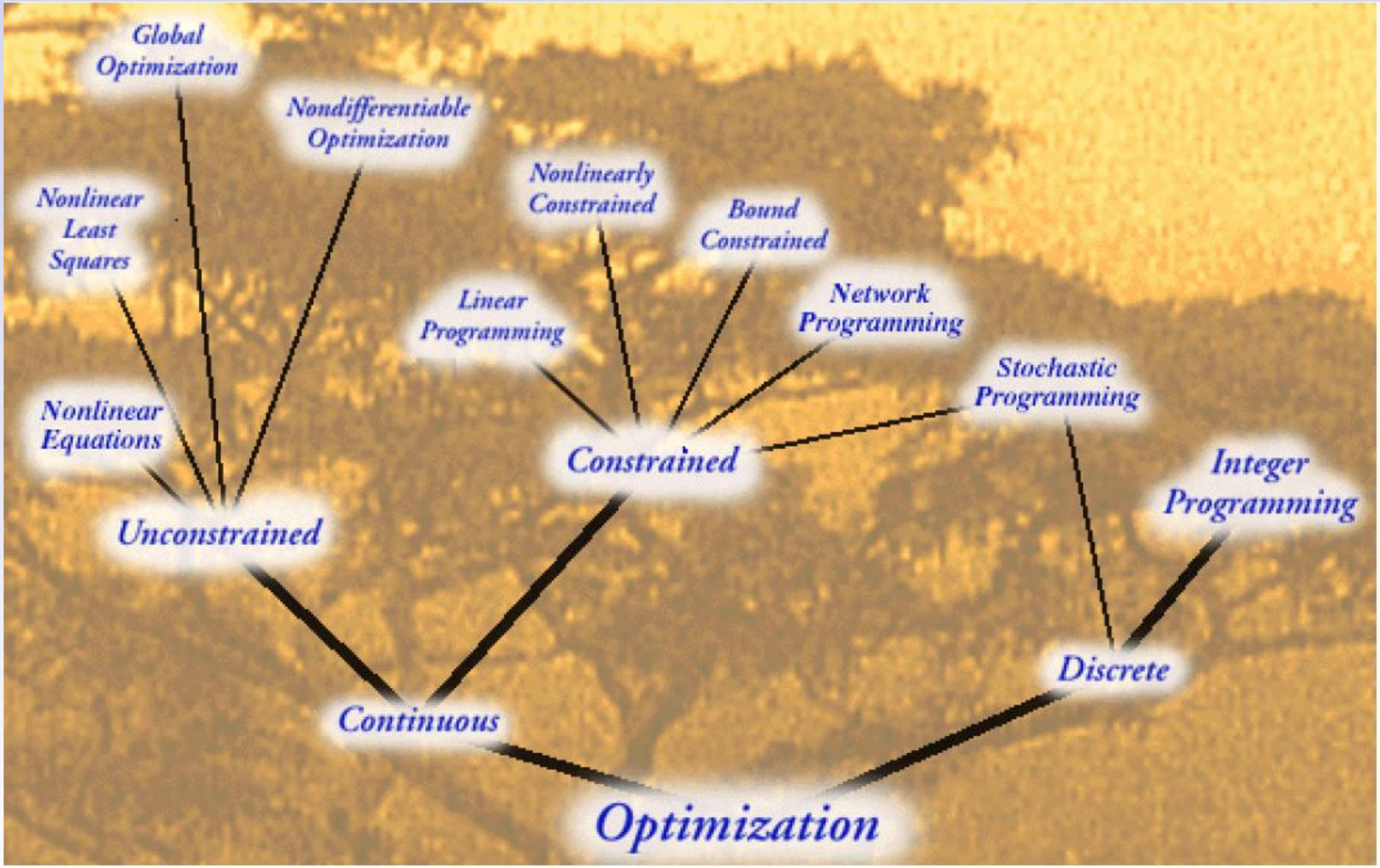




Example

Design for AM

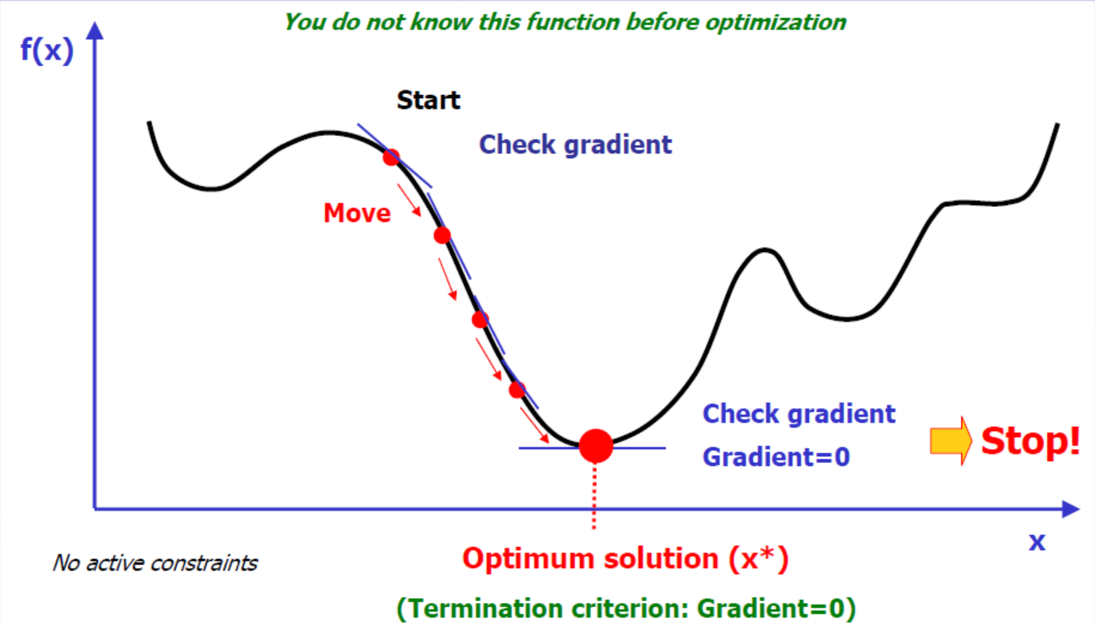
Geometry Optimization – how



Optimization algorithms and methods: (Over 100)
http://en.wikipedia.org/wiki/Category:Optimization_algorithms_and_methods

Design for AM

Geometry Optimization – how



Gradient-based method

UNCONSTRAINED

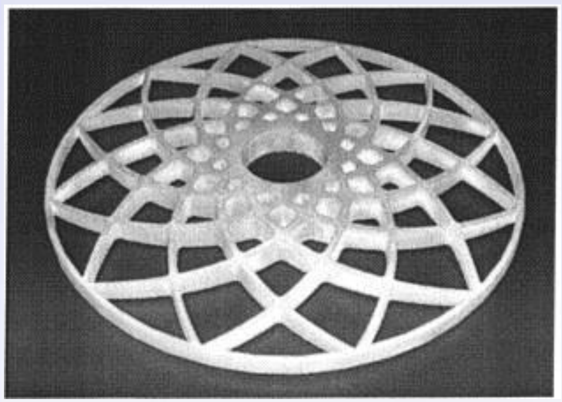
- Steepest Descent
- Conjugate Gradient
- Quasi-Newton
- Newton

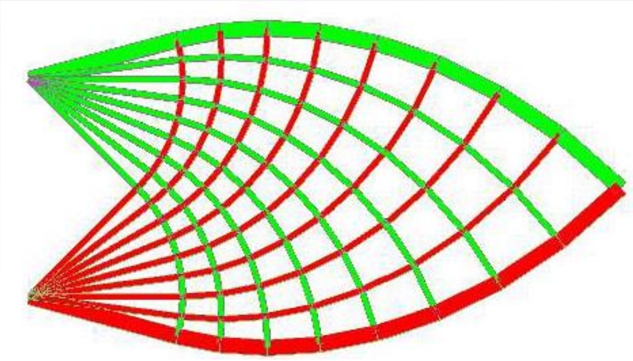
CONSTRAINED

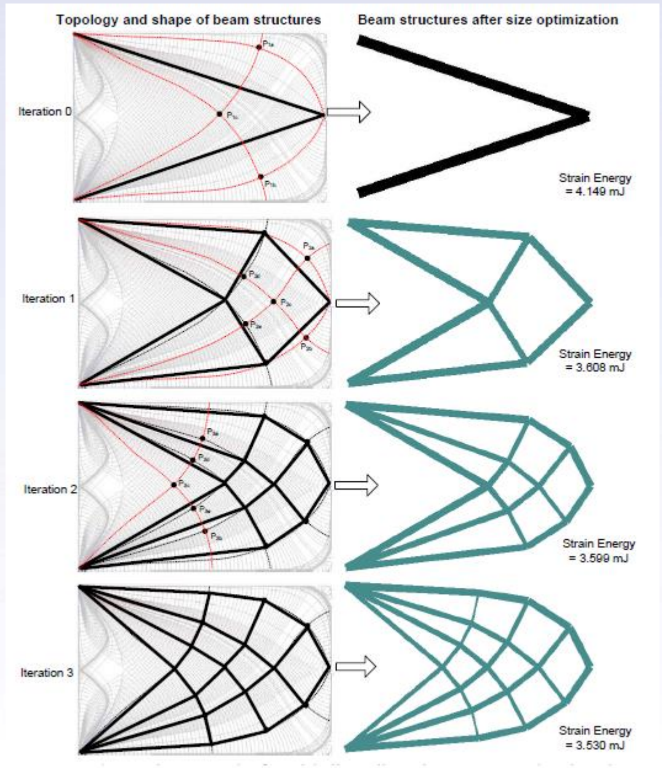
- Simplex – linear
- SLP – linear
- SQP – nonlinear, expensive, common in engineering applications
- Exterior Penalty – nonlinear, discontinuous design spaces
- Interior Penalty – nonlinear
- Generalized Reduced Gradient – nonlinear
- Method of Feasible Directions – nonlinear
- Mixed Integer Programming

Design for AM

- **Geometry Optimization – how**
  - **Michell truss**
    - **Proposed in 1904**
    - **Only tensile and compressive members**
    - **Intersect at right angle**
    - **Corresponds to slip lines (max shear stress)**
    - **Analytical solution (minimum weight for given load)**
    - **Benchmark for code verification**

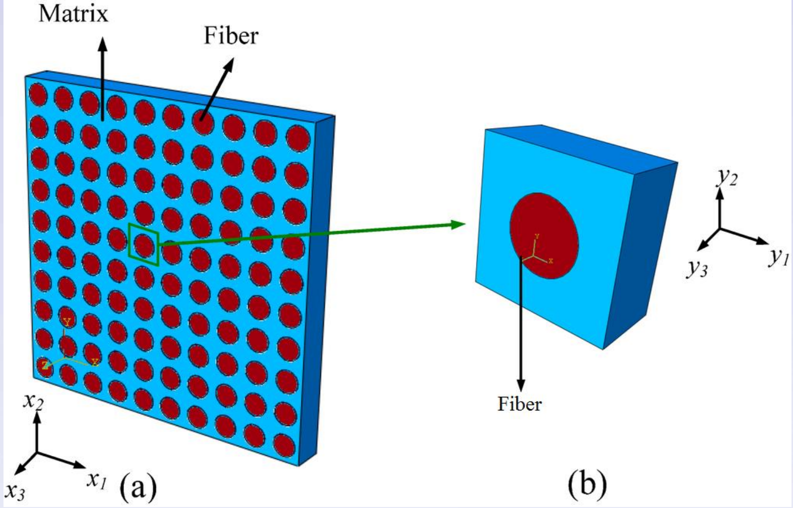




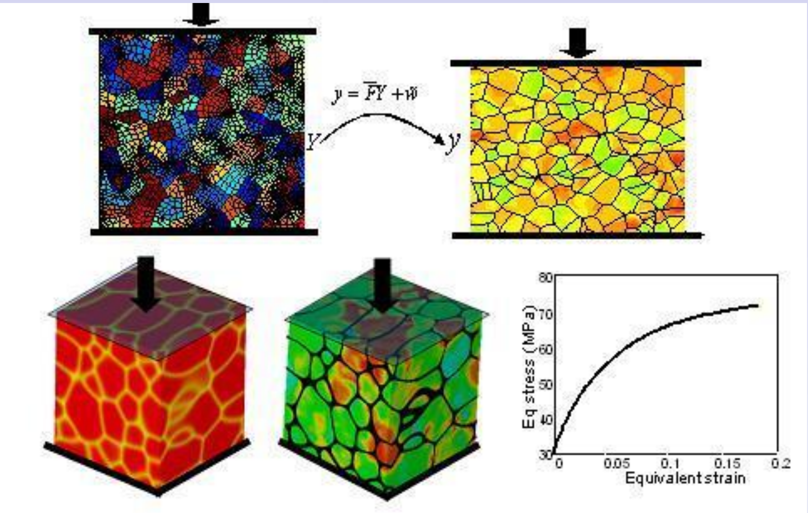


Design for AM

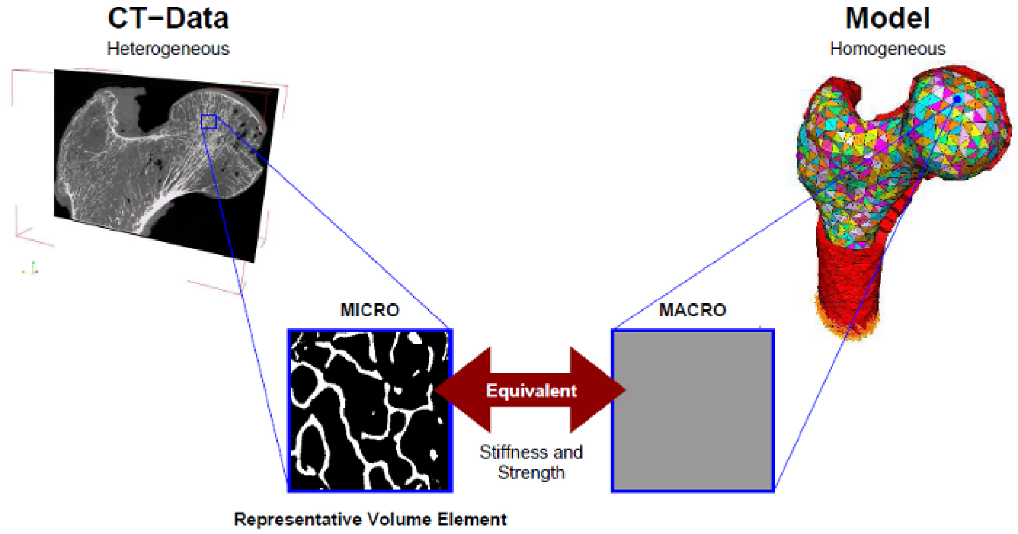
- **Geometry Optimization – how**
  - **Homogenization method**



Homogenization of composite materials



Calculate equivalent stress-strain relationship



Example

Design for AM

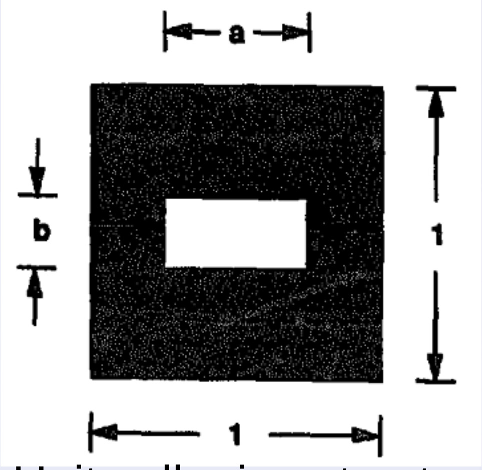
Design

Optimization

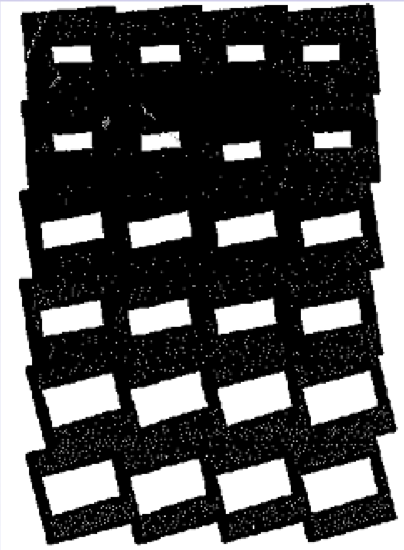
Geometry

Materials

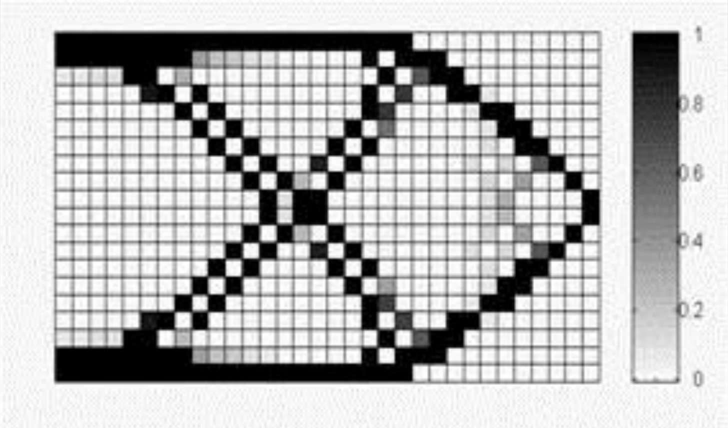
- **Geometry Optimization – how**
  - **Homogenization method**



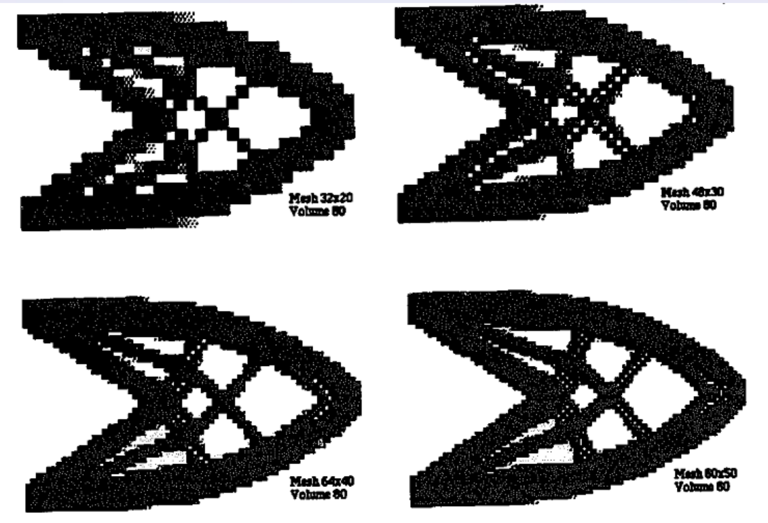
Unit cell microstructure



Change in microstructure



Consider structure as a composite of material and voids (volume fraction)



Convergence of optimal design

Suzuki, Katsuyuki, and Noboru Kikuchi. "A homogenization method for shape and topology optimization." *Computer methods in applied mechanics and engineering* 93.3 (1991): 291-318.

Design for AM

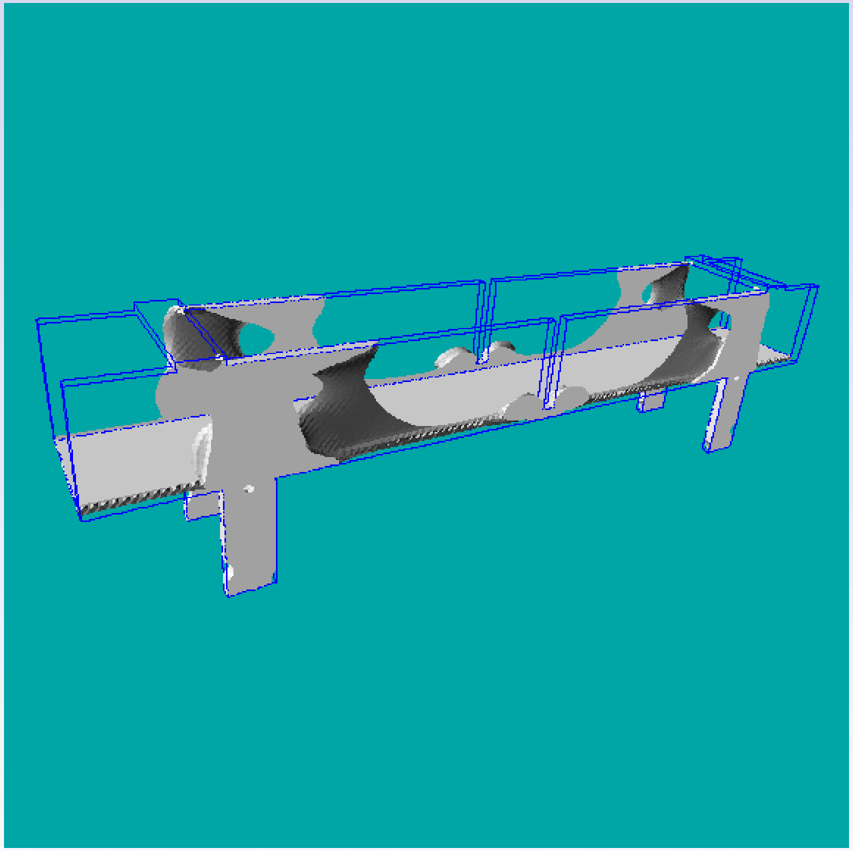
- **Geometry Optimization – how**
  - **Homogenization method**

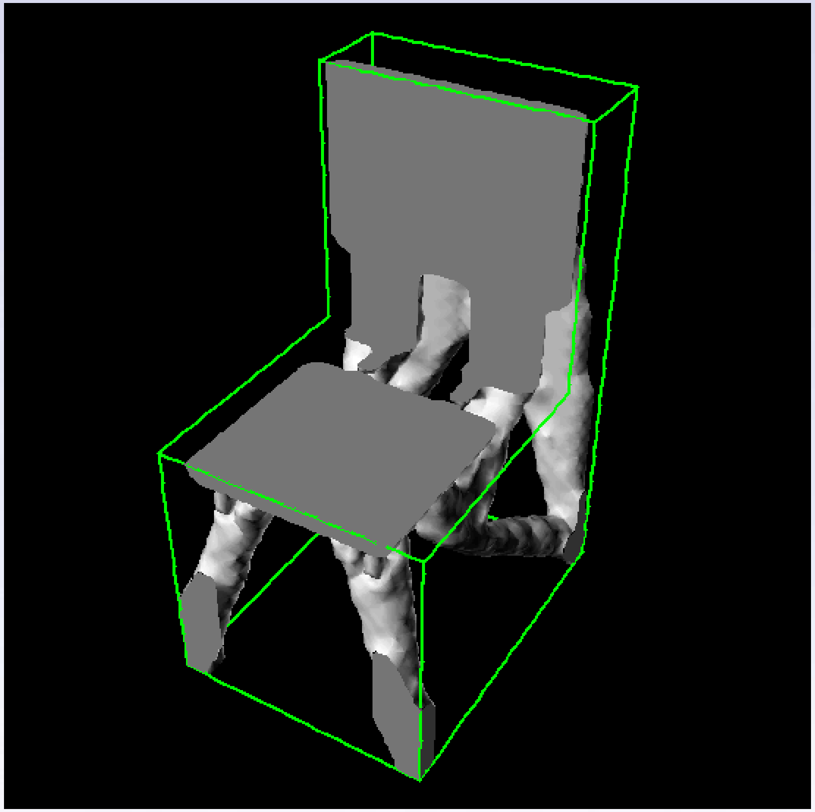
Design

Optimization

Geometry

Materials





http://www.cmap.polytechnique.fr/~optopo/homog_en.html

Design for AM

- **Geometry Optimization – how**
  - **Genetic Algorithm**
    - **A class of probabilistic optimization algorithms**
    - **Inspired by the biological evolution process**
    - **Uses concepts of "Natural Selection" and "Genetic Inheritance" (Darwin 1859)**
    - **Originally developed by John Holland (1975)**
    - **Particularly well suited for hard problems where little is known about the underlying search space**
    - **Widely-used in business, science and engineering**

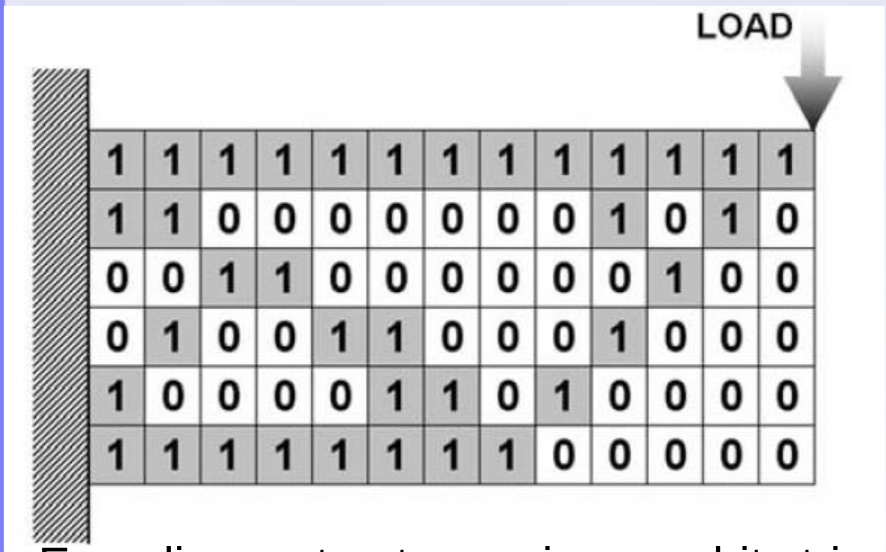
Design for AM

- Geometry Optimization – how
  - Genetic Algorithm – steps
    - Encoding technique (gene, chromosome)
    - Initialization procedure (creation)
    - Evaluation function (environment)
    - Selection of parents (reproduction)
    - Genetic operators (mutation, recombination)
    - Parameter settings (practice and art)

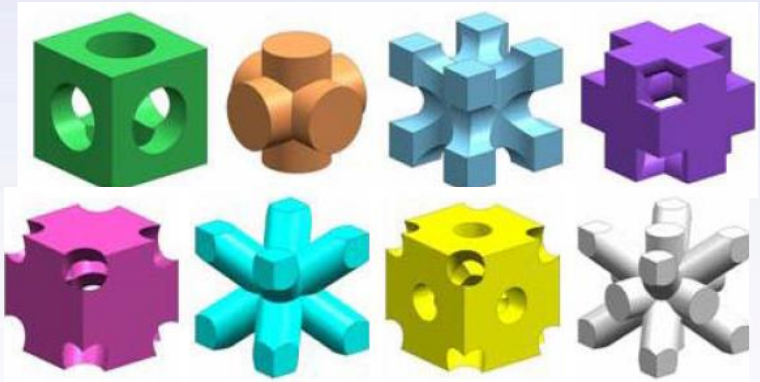
```
{
    initialize population;
    evaluate population;
    while TerminationCriteriaNotSatisfied
    {
        select parents for reproduction;
        perform recombination and mutation;
        evaluate population;
    }
}
```

Design for AM

- **Geometry Optimization – how**
  - **Genetic Algorithm – population**
    - **Bit strings** (0101 … 1100)
    - **Real numbers** (43.2 -33.1 … 0.0 89.2)
    - **Permutations of element** (E11 E3 E7 … E1 E15)
    - **Lists of rules** (R1 R2 R3 … R22 R23)
    - **Program elements** (genetic programming)
    - **… any data structure …**



Encode with multiple materials

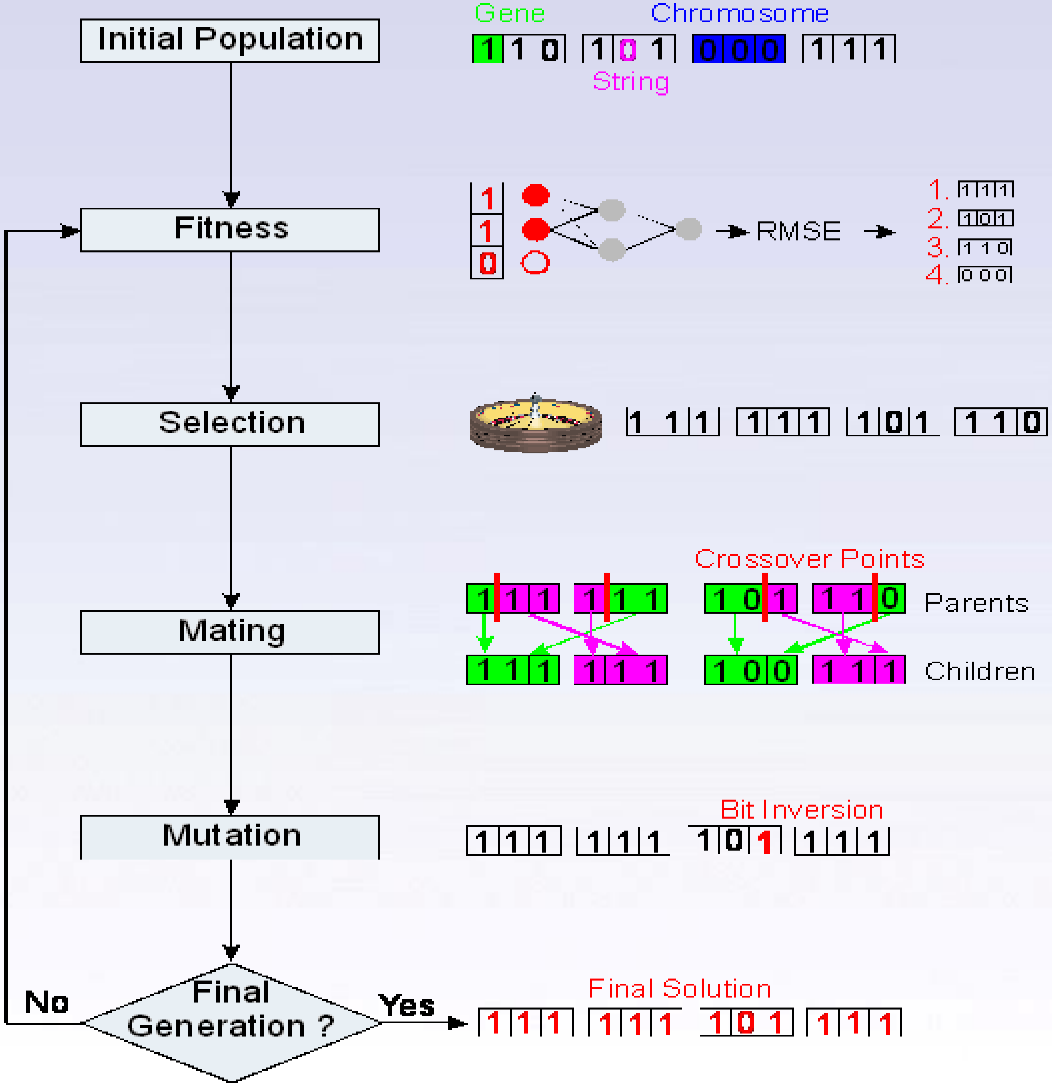


Encoding a structure using one bit string: structure – phenotype; bit string – genotype. One bit string (individual) is a design solution

Other types of cell structure (bit)

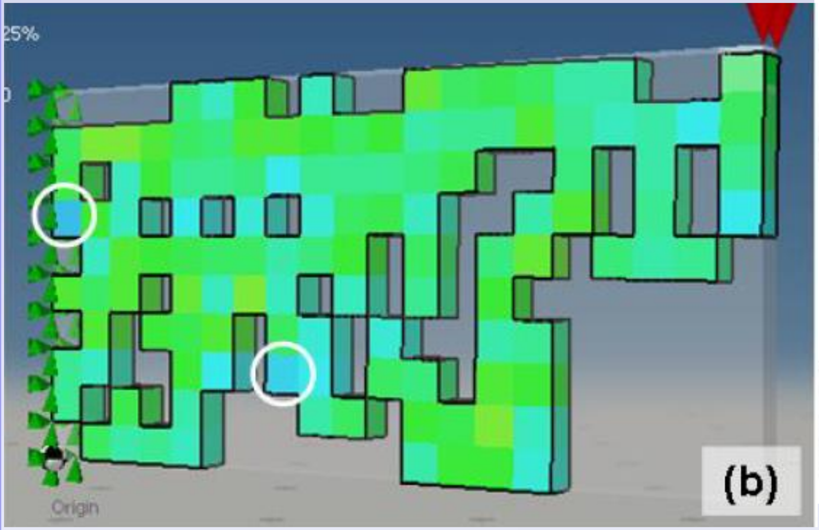
Design for AM

- **Geometry Optimization – how**
  - **Genetic Algorithm – architecture**

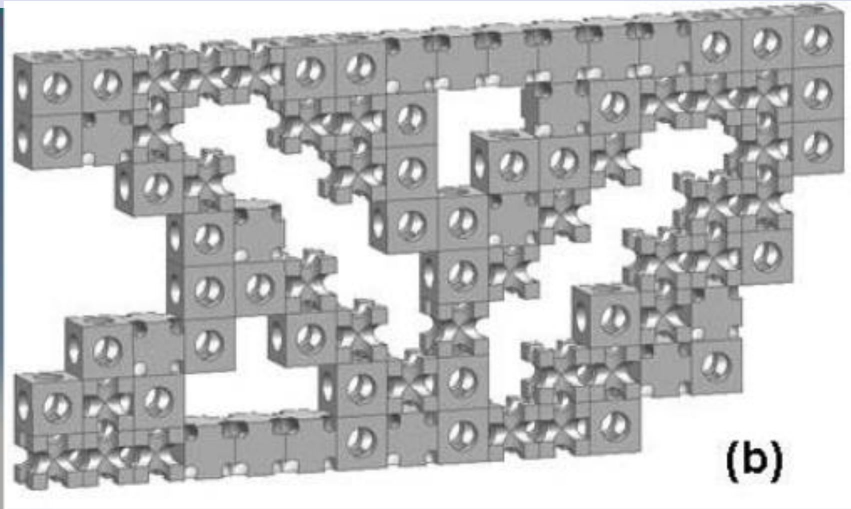


Design for AM

- Geometry Optimization – how
  - Genetic Algorithm – results



Cantilever Beam Result from DesignLab for a Single Material with Areas of Local High and Low Stress Circled



Possible Cantilever Beam Geometry Created From Three Cellular Structures each with 50% Volume Fractions

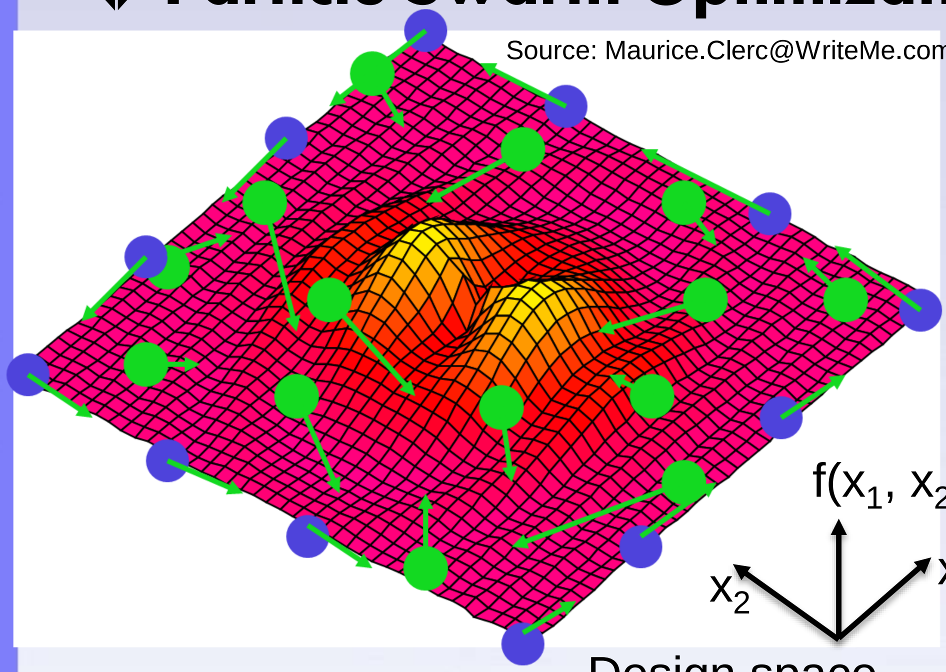
Source: Watts, Darren M., and Richard JM Hague. "Exploiting the design freedom of RM." (2006).

Design for AM

Advanced Manufacturing | Modeling | Materials

- Design
- Optimization
  - Geometry
- Materials

- **Geometry Optimization – how**
  - **Particle Swarm Optimization**



Design space

Eq. (a):
v[] = c0 *v[] + c1 * rand() * (pbest[] - present[]) + c2 * rand() * (gbest[] - present[])

Eq. (b):
present[] = present[] + v[]

- **Each particle is a design**
- **Each particle is moving in the design space with a velocity V in search for optimal**
- **Each particle remembers its personal best**
- **Particle V depends on its current V, the positions of the global best, position of its personal best, and maybe best neighbour**

Design for AM

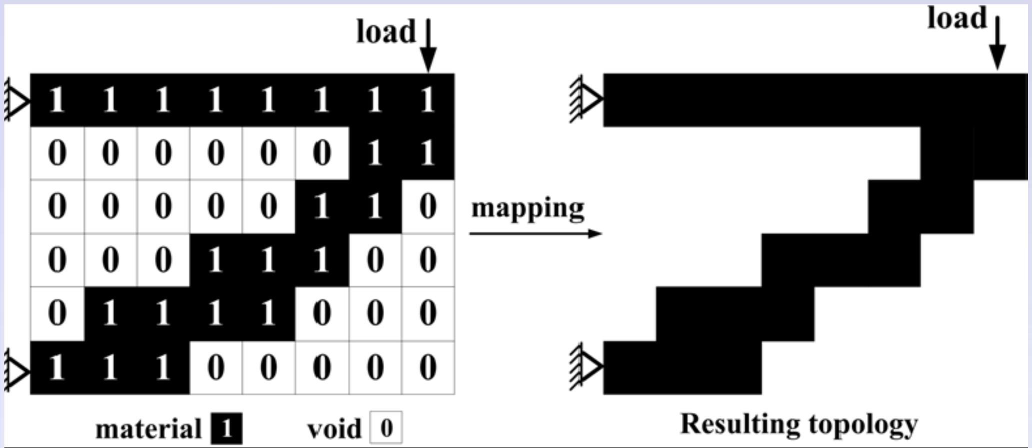
- **Geometry Optimization – how**
  - **Particle Swarm Optimization**


```
For each particle
    Initialize particle
END

Do
    For each particle
        Calculate fitness value
        If the fitness value is better than its peronal best
            set current value as the new pBest
    End

    Choose the particle with the best fitness value of all as gBest
    For each particle
        Calculate particle velocity according equation (a)
        Update particle position according equation (b)
    End
While maximum iterations or minimum error criteria is not attained
```

Design for AM

Geometry Optimization – how

- **Particle Swarm Optimization – Binary for topology optimization**



Eq. (a):

$$V_i^{k+1} = \mathbf{c}_1 \otimes \left(P_{best,i}^{k} \oplus X_i^{k} \right) + \mathbf{c}_2 \otimes \left(G_{best}^{k} \oplus X_i^{k} \right)$$

Eq. (b):

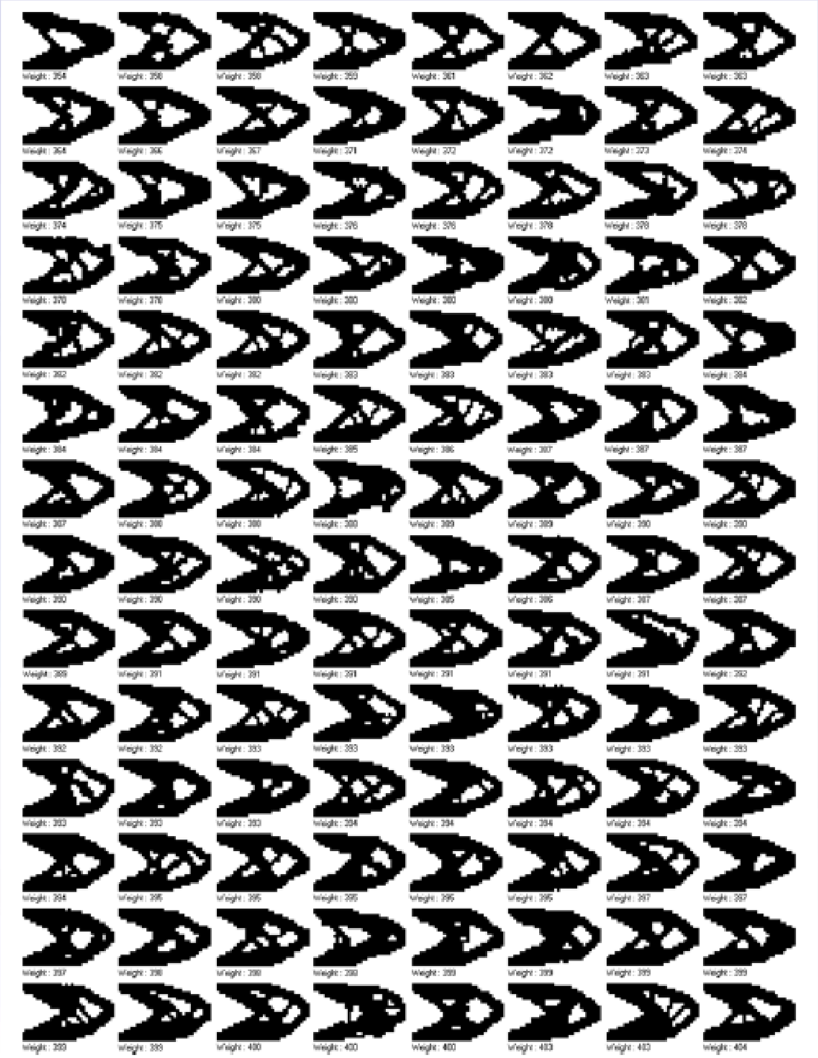
$$X_i^{k+1} = X_i^{k} \oplus V_i^{k+1}$$

$\otimes$ (AND) $\oplus$ (XOR)

Luh, Guan-Chun, and Chun-Yi Lin. "A Binary Particle Swarm Optimization for Structural Topology Optimization."

Design for AM

- **Geometry Optimization – how**
  - **Particle Swarm Optimization – example results**



Luh, Guan-Chun, and Chun-Yi Lin. "A Binary Particle Swarm Optimization for Structural Topology Optimization."

Design for AM

Advanced Manufacturing | Modeling | Materials

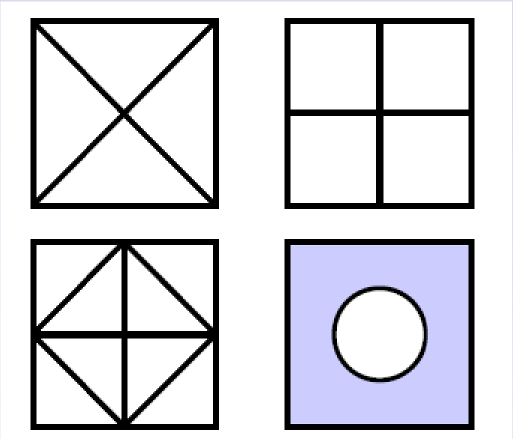
Design

Optimization

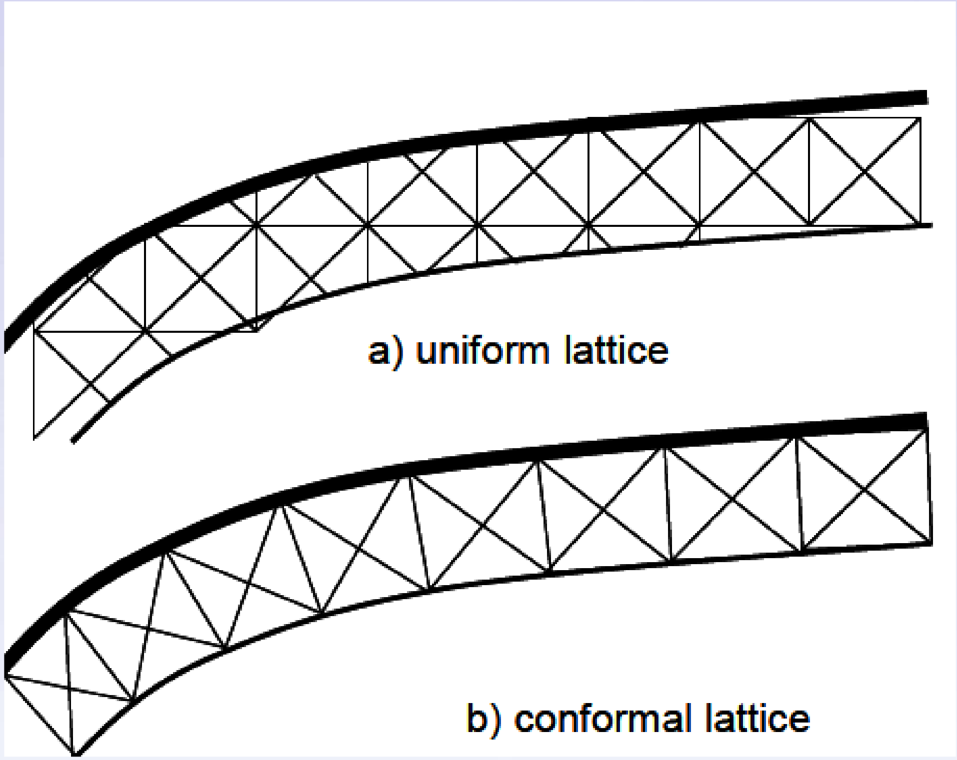
Geometry

Materials

- Geometry Optimization – how
  - Cellular structure



Cell types



Ground structures

Topology optimization → **Size optimization**

Credit: Jason Nguyen MS thesis

Design

Optimization

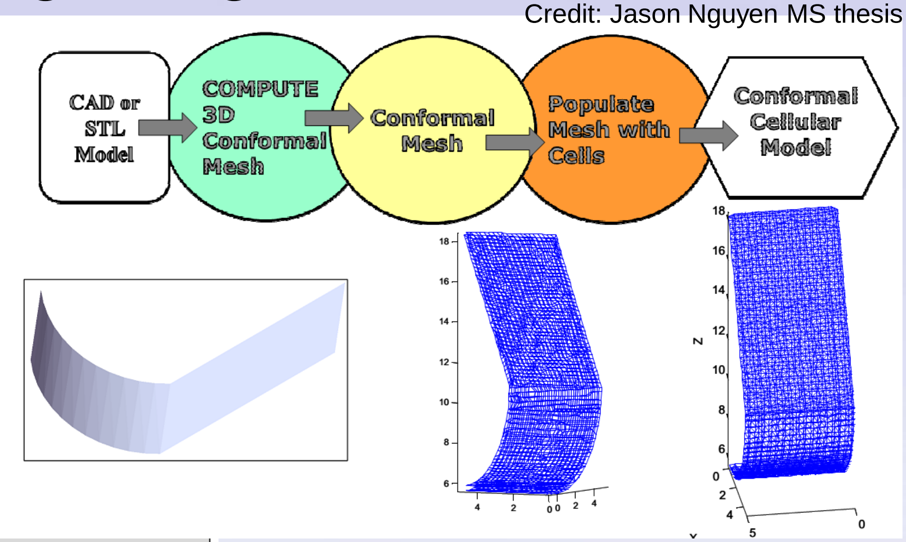
Geometry

Materials

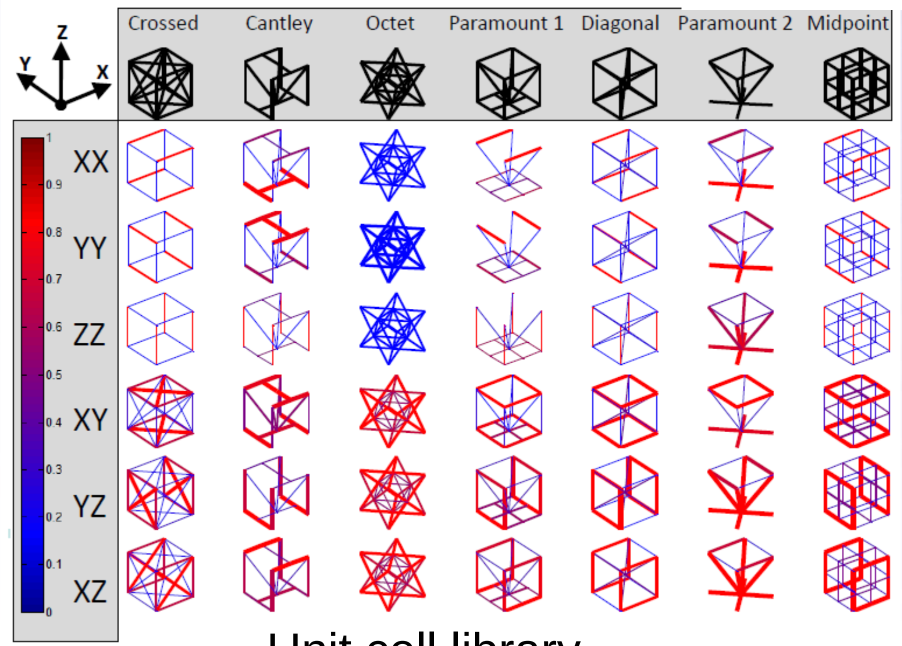
Design for AM

- Geometry Optimization – how
  - Cellular structure

Credit: Jason Nguyen MS thesis



Generate ground structure

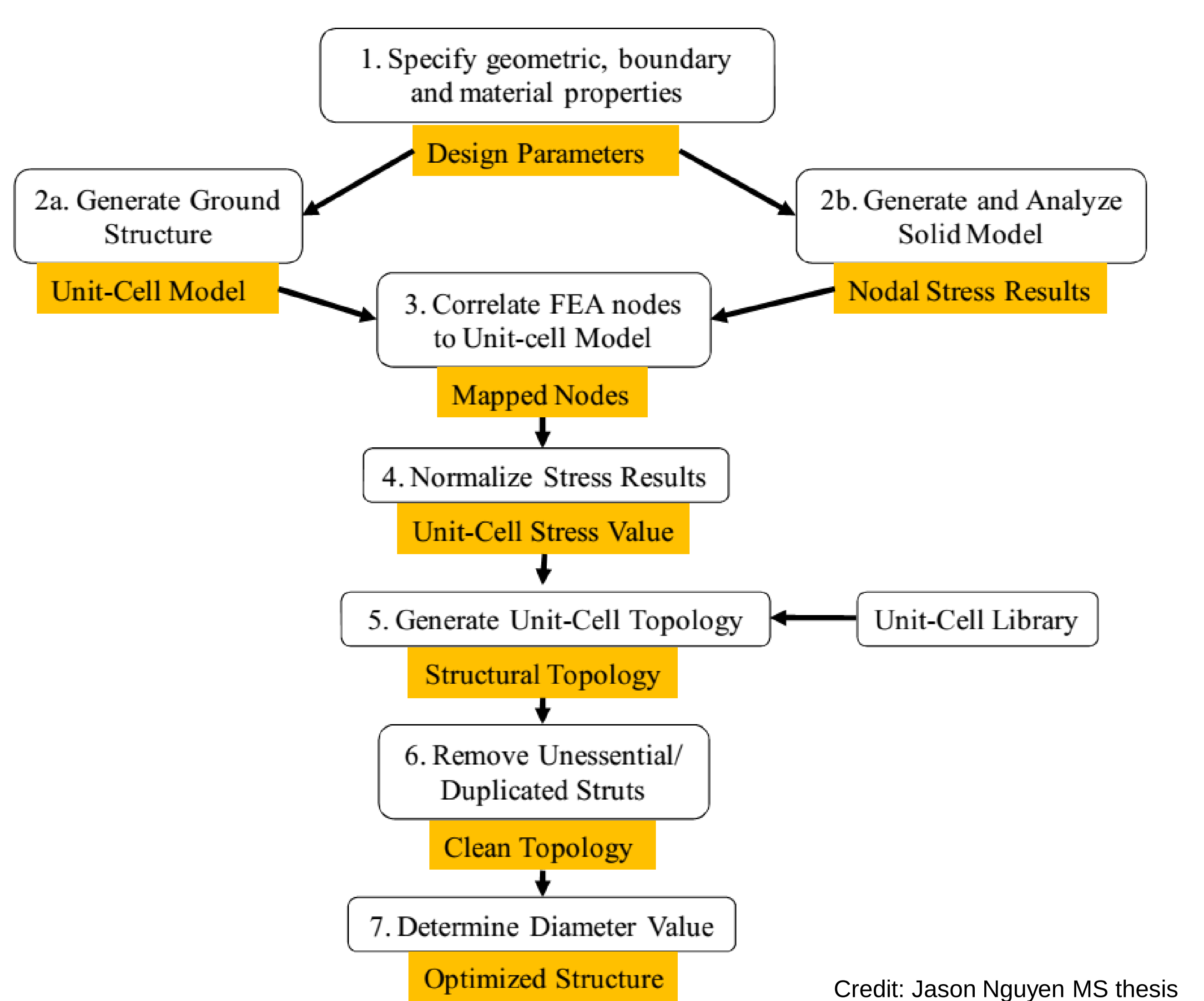


Unit cell library

Credit: Patrick Chang MS thesis

Design for AM

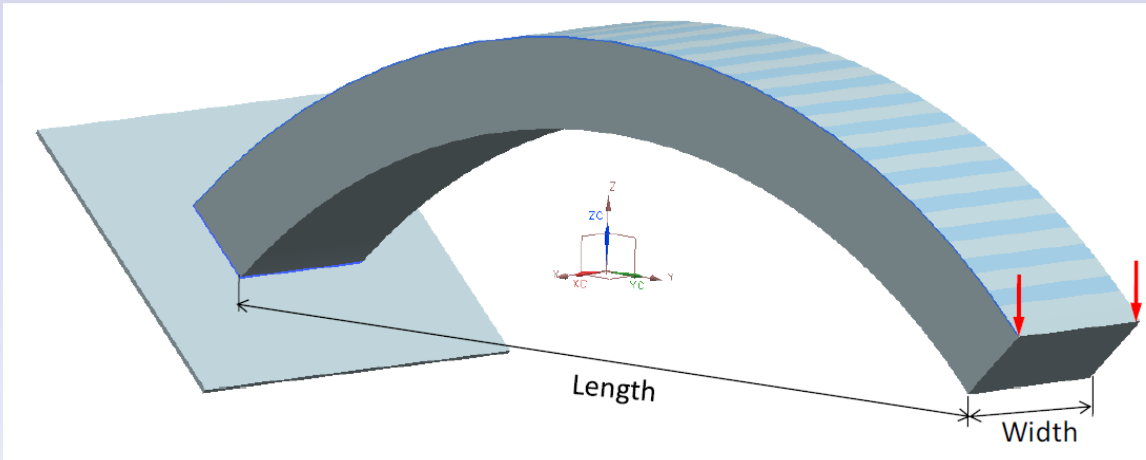
- Geometry Optimization – how
  - Cellular structure



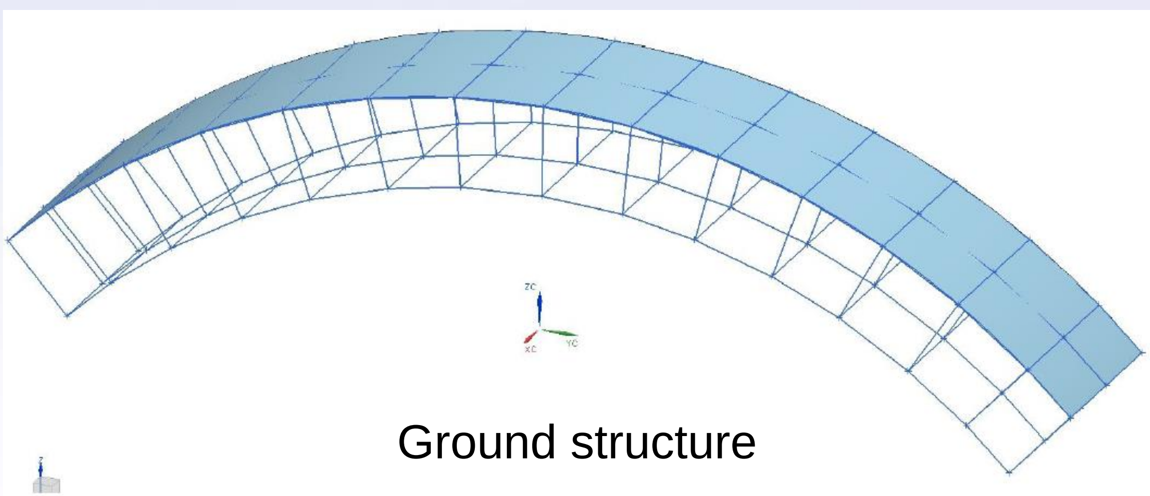
Credit: Jason Nguyen MS thesis

Advanced Manufacturing | Modeling | Materials

- Geometry Optimization – how
  - Cellular structure



Problem



Ground structure

Design

Optimization

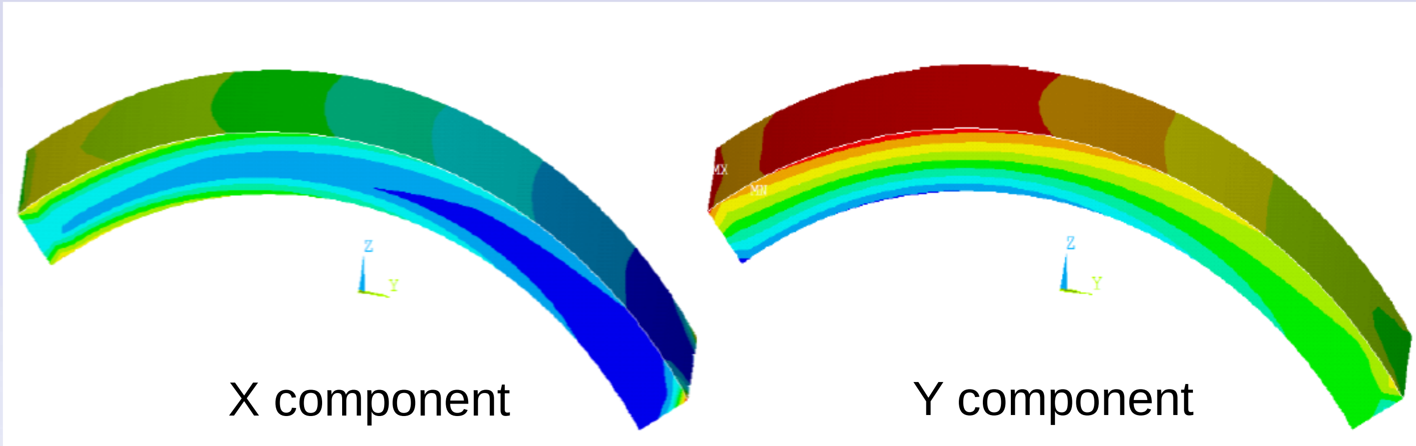
Geometry

Materials

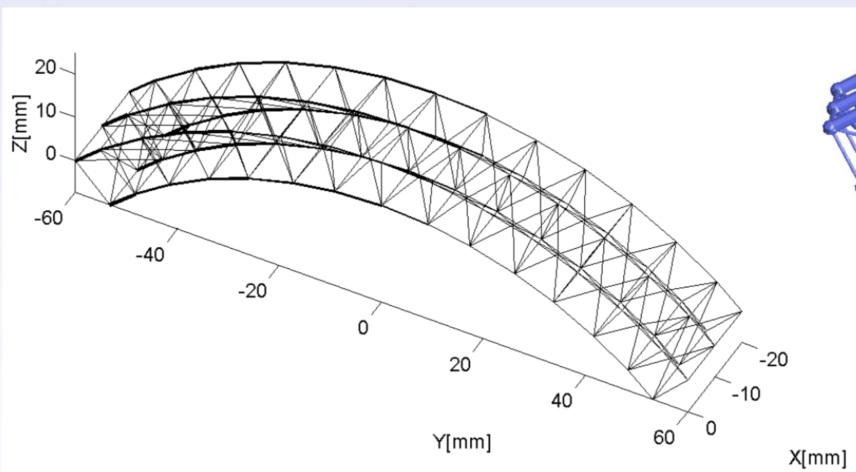
Credit: Jason Nguyen MS thesis

Design for AM

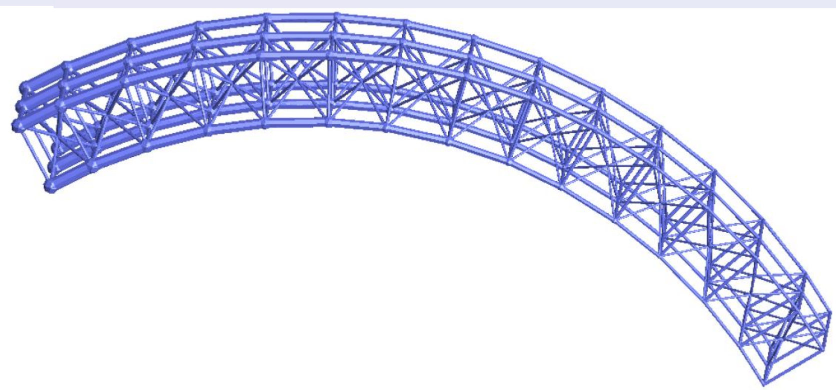
- **Geometry Optimization – how**
  - **Cellular structure**



Solid body analysis



Scaling and mapping with unit cell



Final topology

Credit: Jason Nguyen MS thesis

Design for AM

Design

Optimization

Geometry

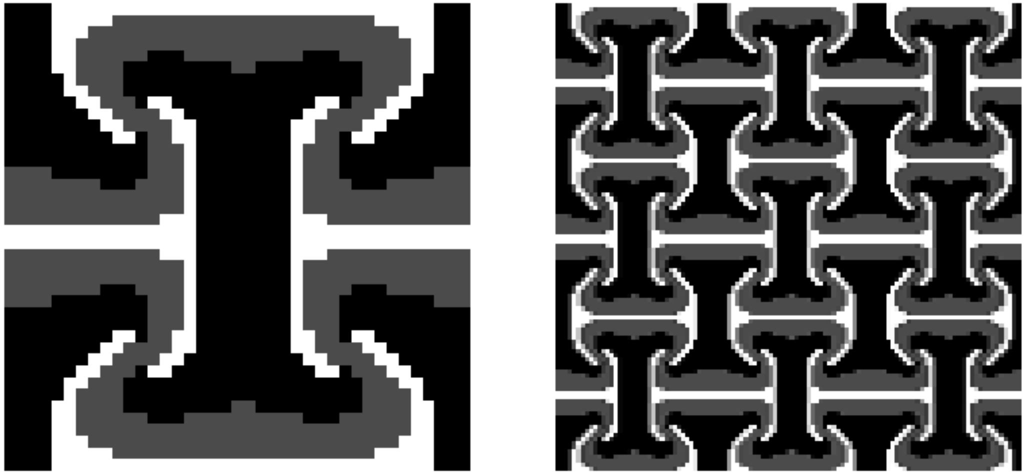
Materials

Material design

Multi-material 3D printers: Objet Connex (inkjet)

Design for AM

Material design



(a) Unit cell mesh 40×40 (b) Array 3 × 3

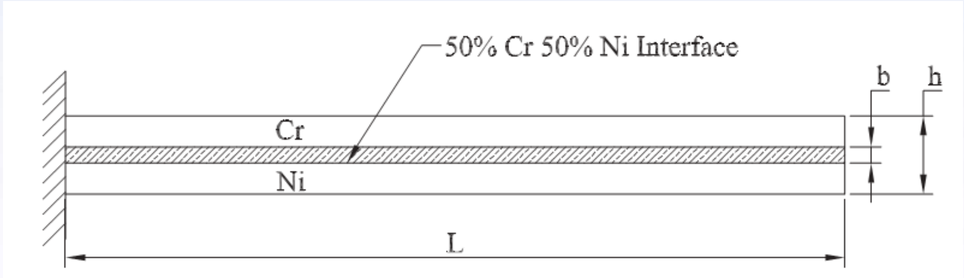
- Mat 1: E =1; ν=0.3; α=1
- Mat 2: E =1; ν=0.3; α=10
- Mat 3: Void (E = 1e-4)

Homogenized property

$$\mathbf{E}^H = 0.01 \begin{bmatrix} 3.51 & -0.59 & 0 \\ -0.59 & 4.85 & 0 \\ 0 & 0 & 0.96 \end{bmatrix},$$

$$\boldsymbol{\alpha}^H = \begin{bmatrix} -6.276 & 0 \\ 0 & -6.529 \end{bmatrix}.$$

Designed material microstructure that has negative thermal expansion coefficient using homogenization method

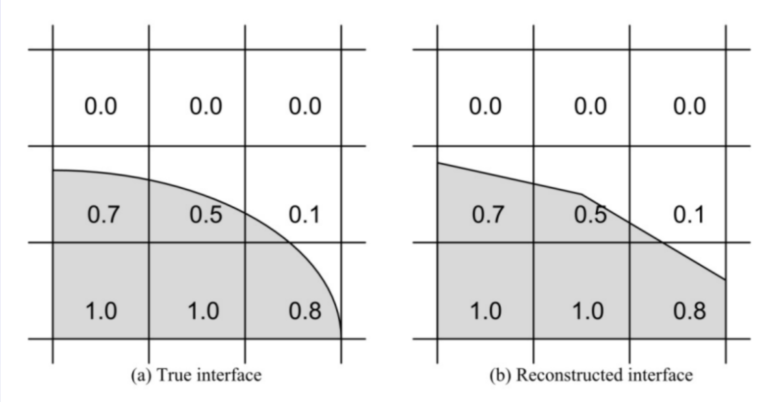


Qi, H., N. Kikuchi, and J. Mazumder. "Interface study and boundary smoothing on designed composite material microstructures for manufacturing purposes."*Structural and multidisciplinary Optimization* 26.5 (2004): 326-332.

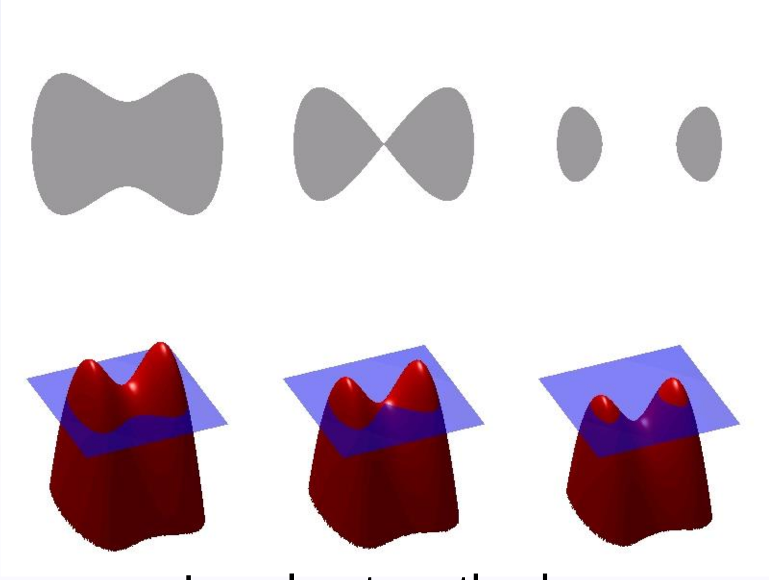
Interface has energy: need to consider interface thickness for homogenization method

Design for AM

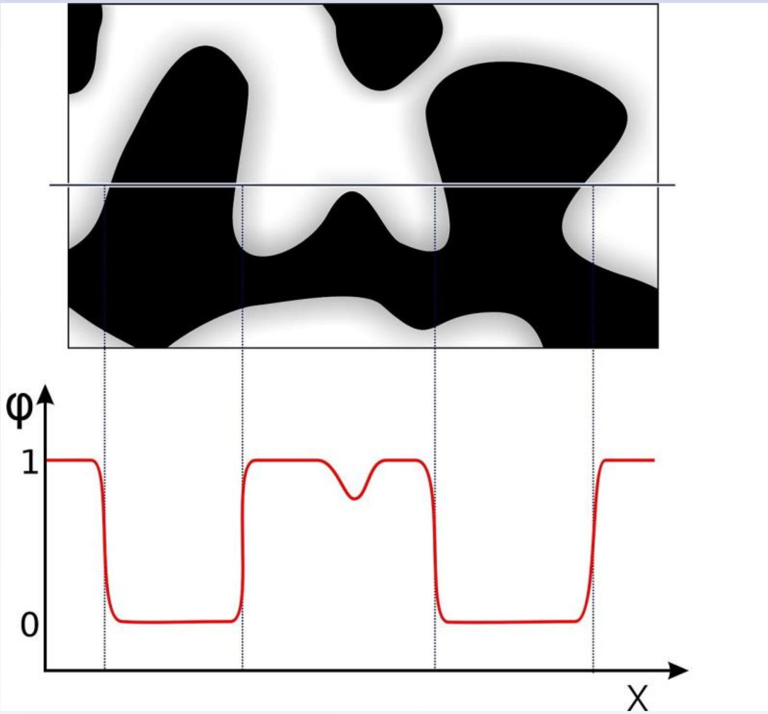
Material design – interface modeling



Volume of Fraction



Level-set method

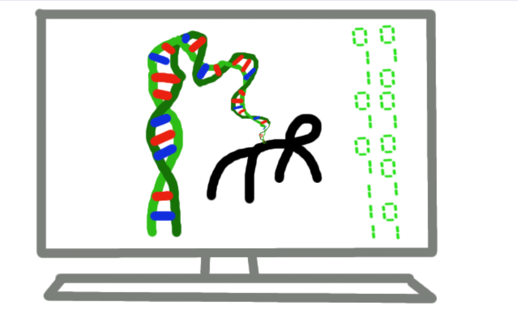


Phase-field method

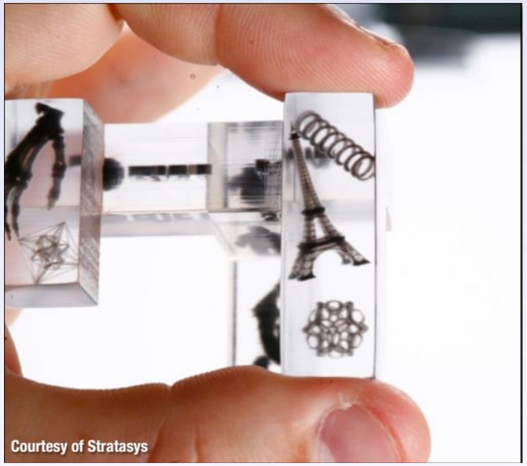
Refer to Zhou, Wenchao. "Interface dynamics in inkjet deposition." (2014).chapter 2 for more details

Design for AM

Material design

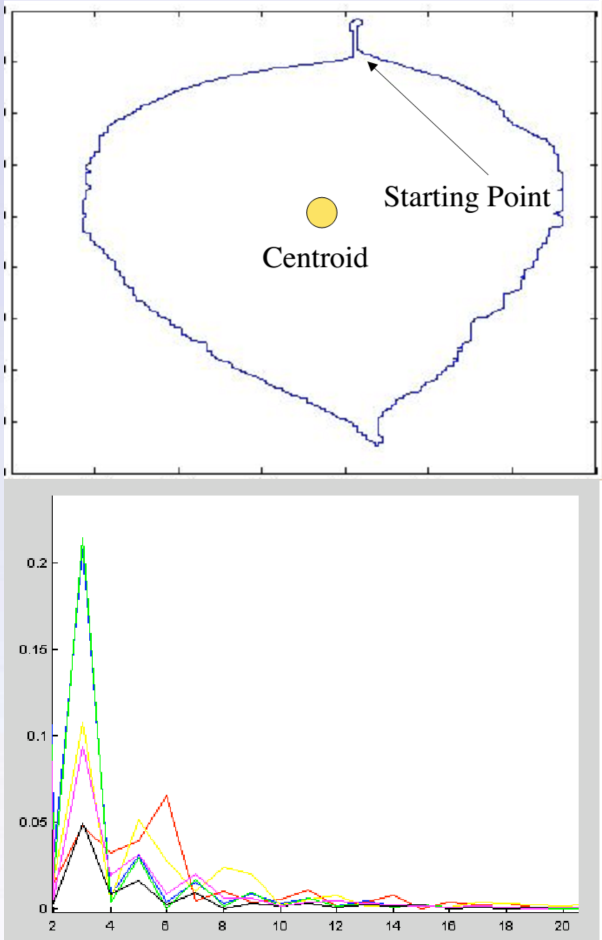


Genetic algorithm for multi-material design

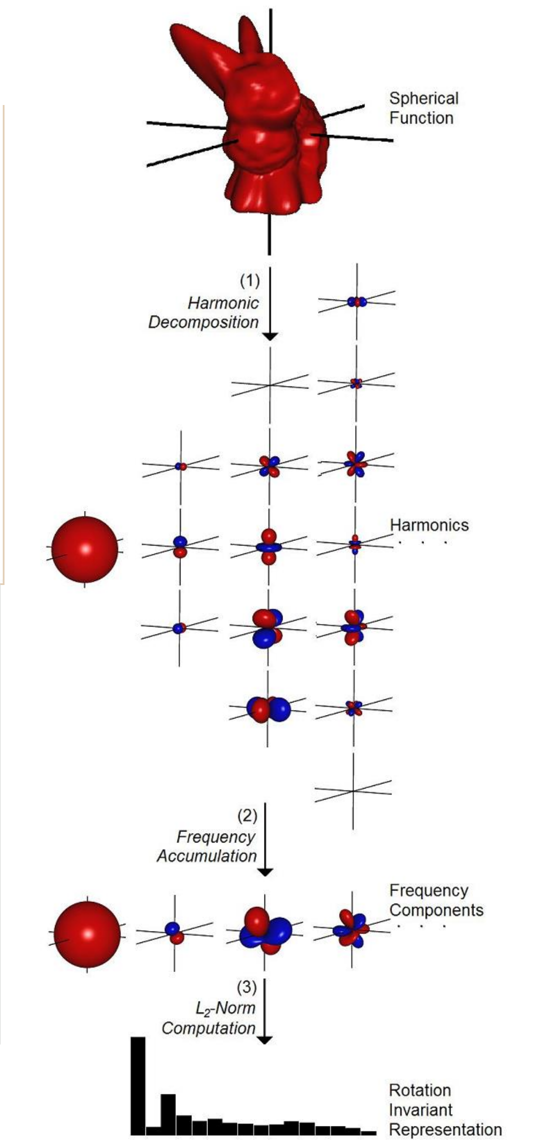


High resolution: 600dpi
~10^8 voxels per cubic inch

Other encoding techniques



Fourier descriptor



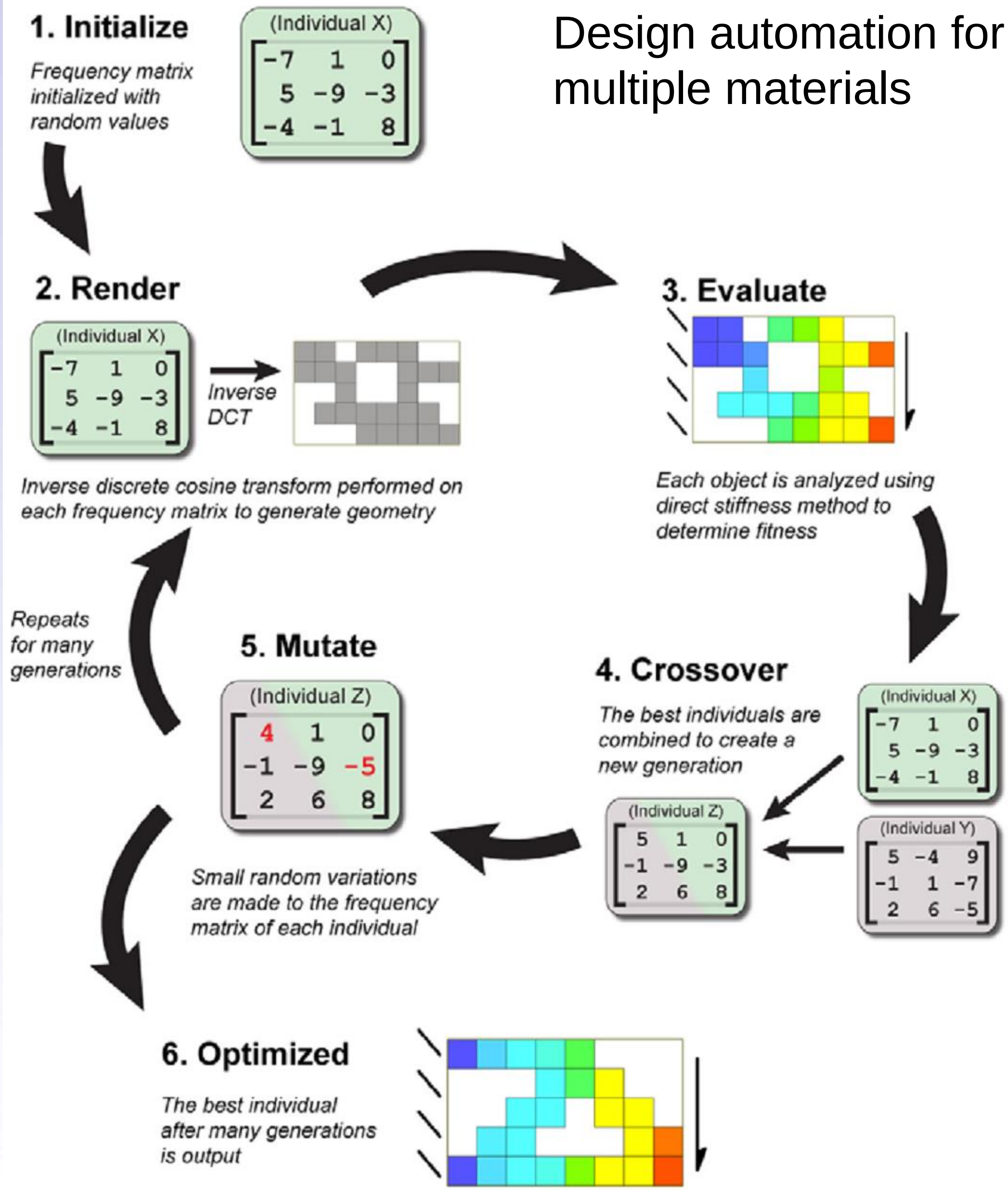
Spherical harmonics

Refer to Zhou, Wenchao. "Interface dynamics in inkjet deposition." (2014).chapter 2 for more details

Design for AM

- **Material design**

Design automation for multiple materials



Hiller, Jonathan D., and Hod Lipson. "Design automation for multi-material printing." *20th Annual International Solid Freeform Fabrication Symposium, Austin, TX, Aug*. 2009.

Design

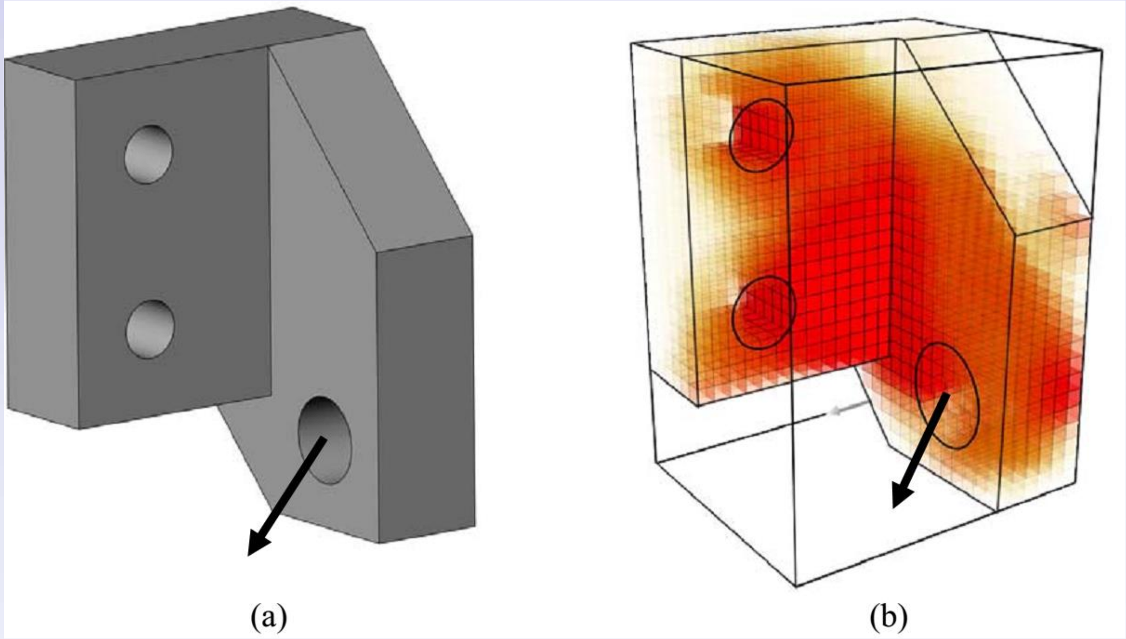
Optimization

Geometry

Materials

Design for AM

Material design



The design automation algorithm optimizes the internal material distribution of a pre-designed bracket (a), in order to maximize stiffness and minimize weight. The results are shown in (b), where red represents stiff, dense material transitioning to transparent yellow, which represents flexible, lightweight material.

Hiller, Jonathan D., and Hod Lipson. "Design automation for multi-material printing." *20th Annual International Solid Freeform Fabrication Symposium, Austin, TX, Aug*. 2009.

Design for AM

Design

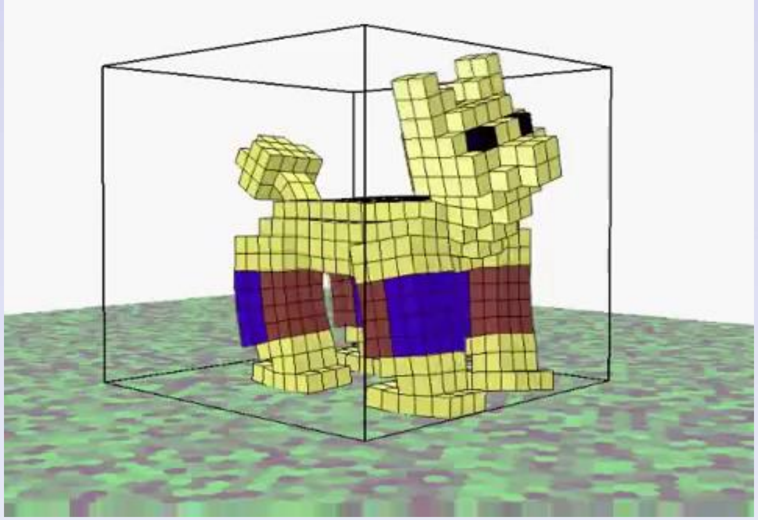
Optimization

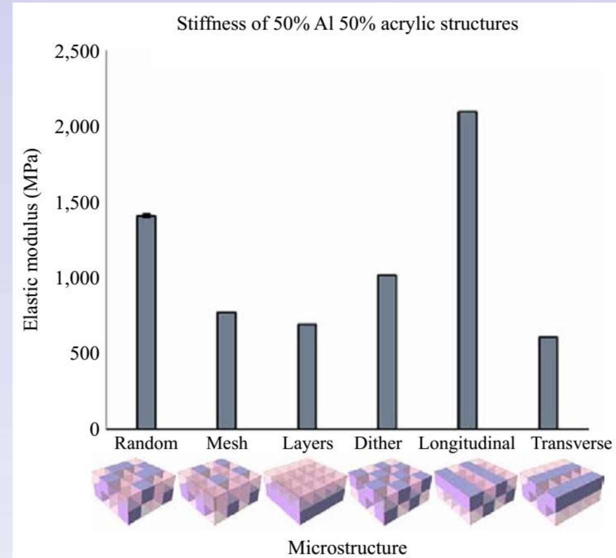
Geometry

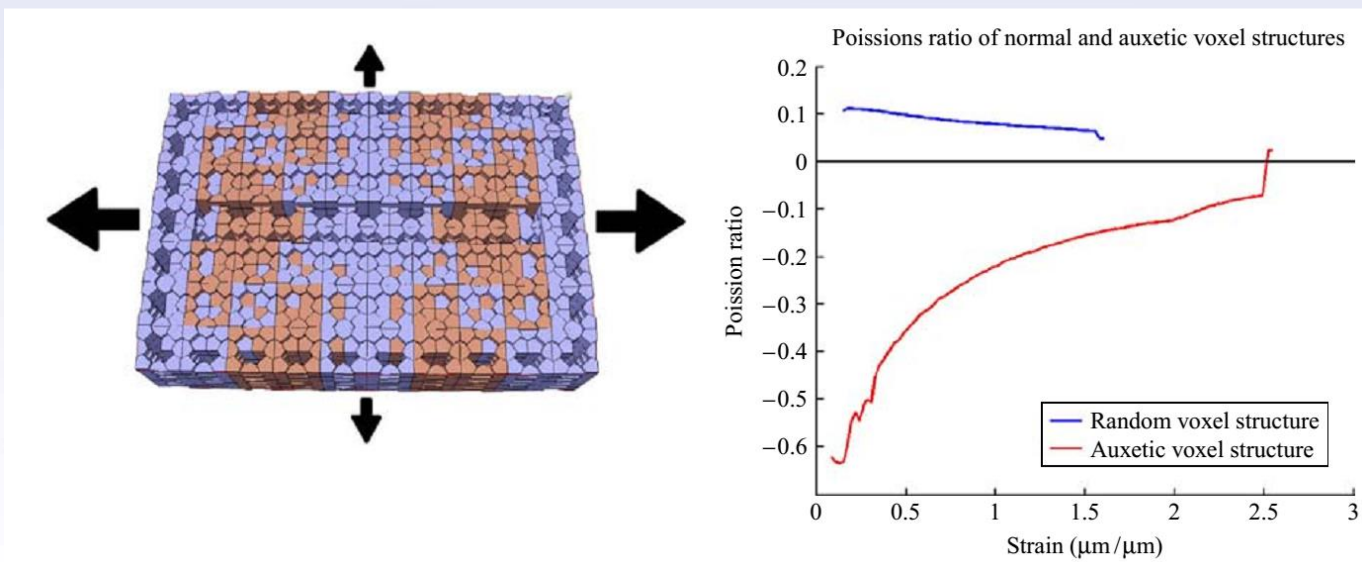
Materials

Material design – digital materials

http://www.voxcad.com/



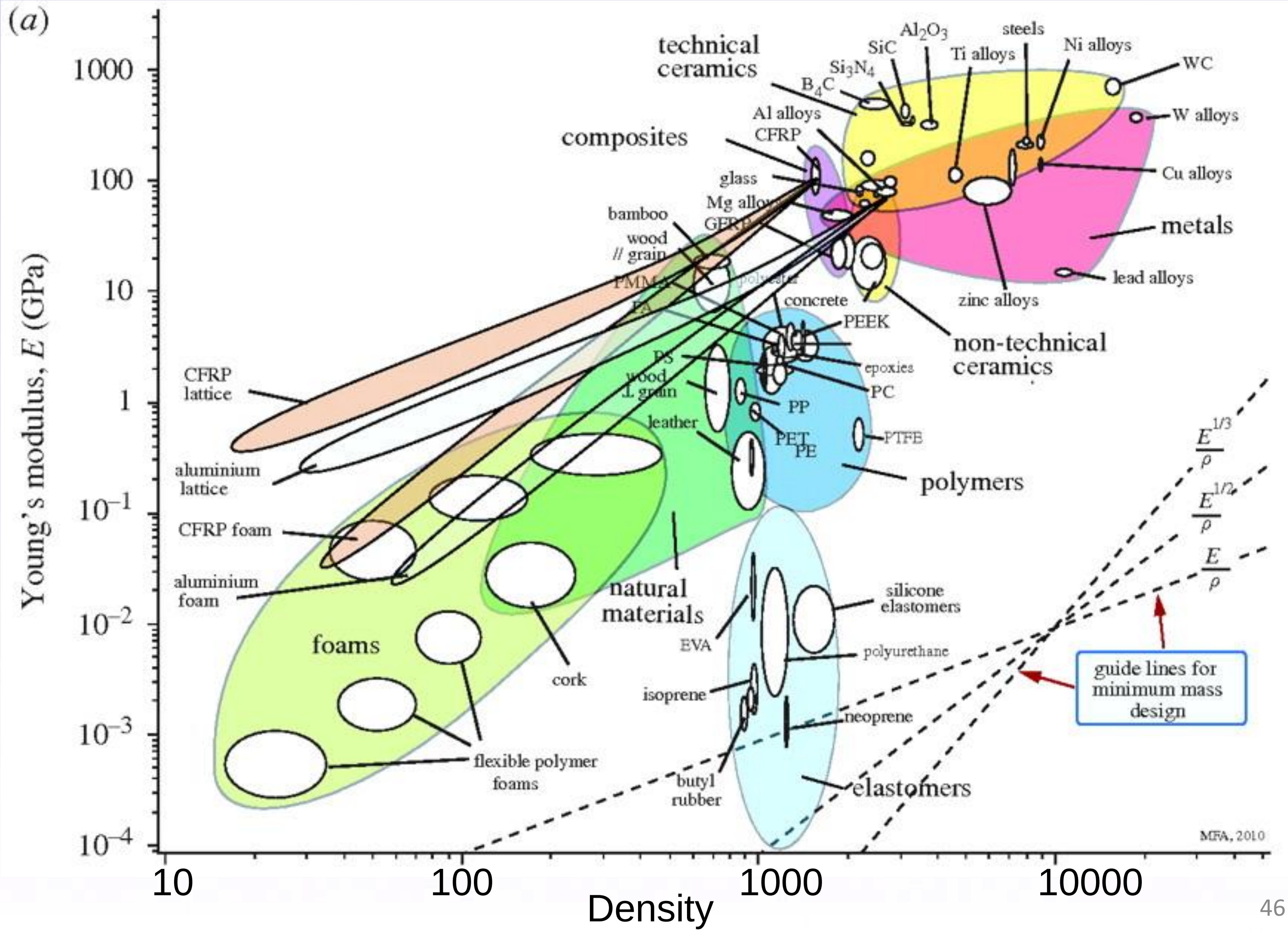




Hiller, Jonathan, and Hod Lipson. "Tunable digital material properties for 3D voxel printers." Rapid Prototyping Journal 16.4 (2010): 241-247.

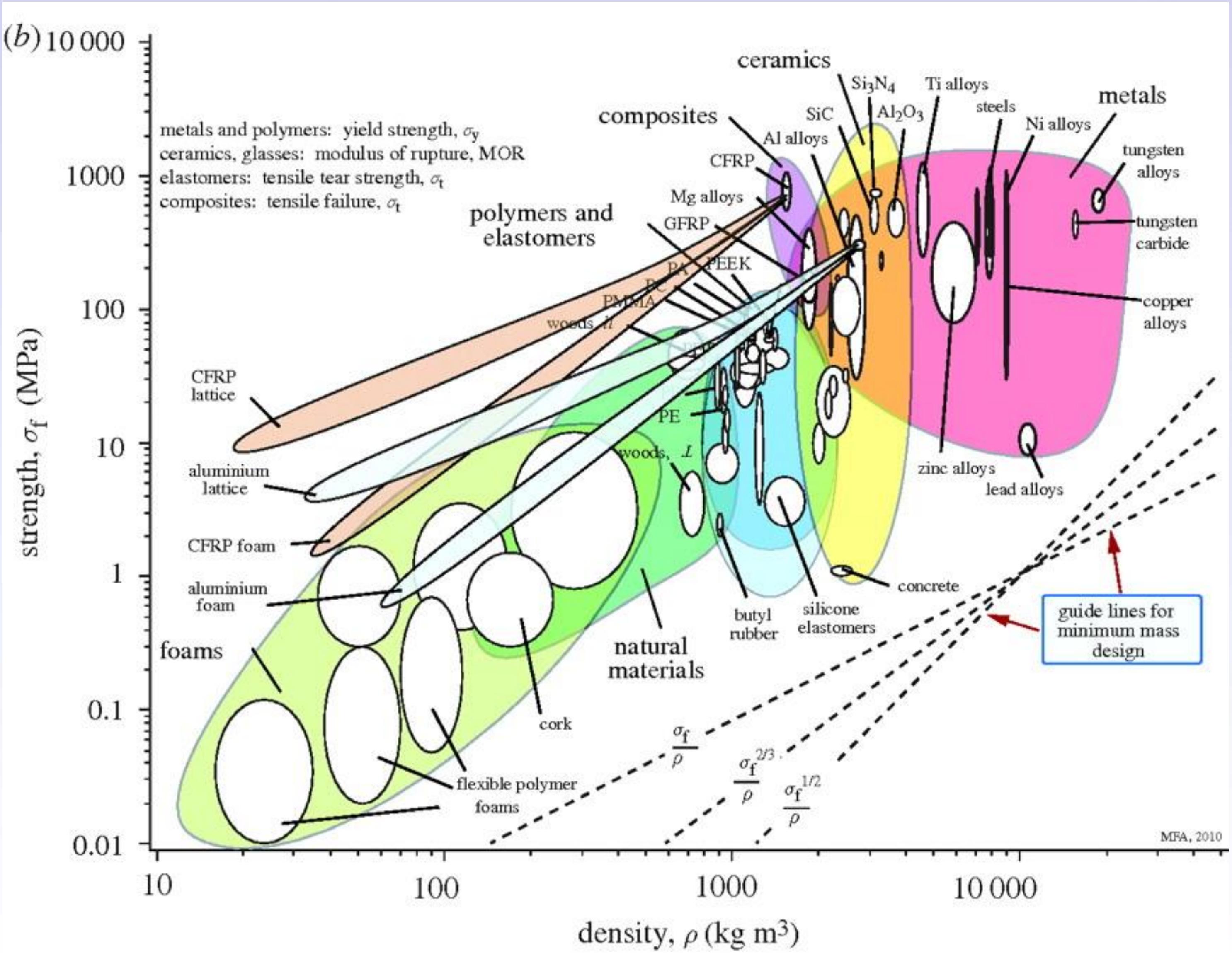
Design for AM

Material design – Ashby Chart



Design for AM

- **Material design – digital materials**



Design for AM

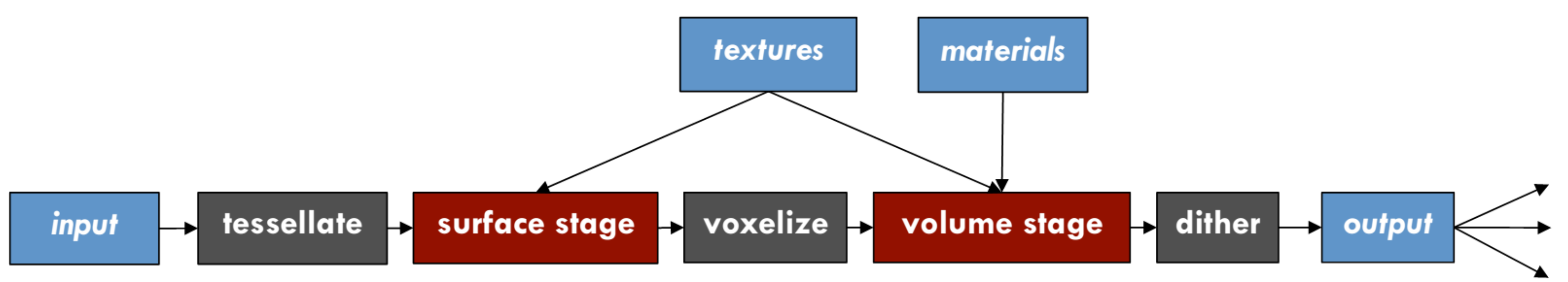
- **Material design – how to fabricate**
  - **File Format – AMF**

```
<?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>
```

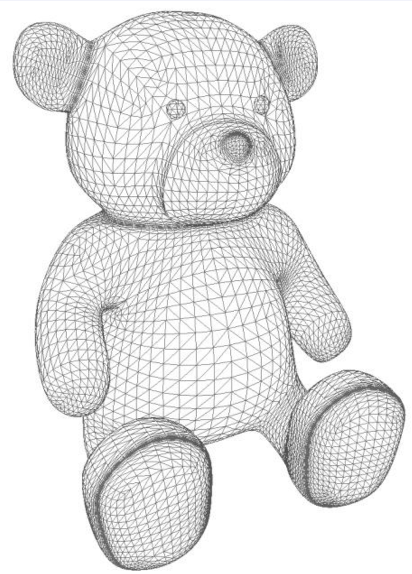
- **Additive Manufacturing File**
- **ISO/ASTM Standard, 2011**
- **Machine independent (no layer or process information)**
- **XML-based format**
  - <object>: volume of materials
  - <material>
  - <texture>
  - <metadata>
  - …

Design for AM

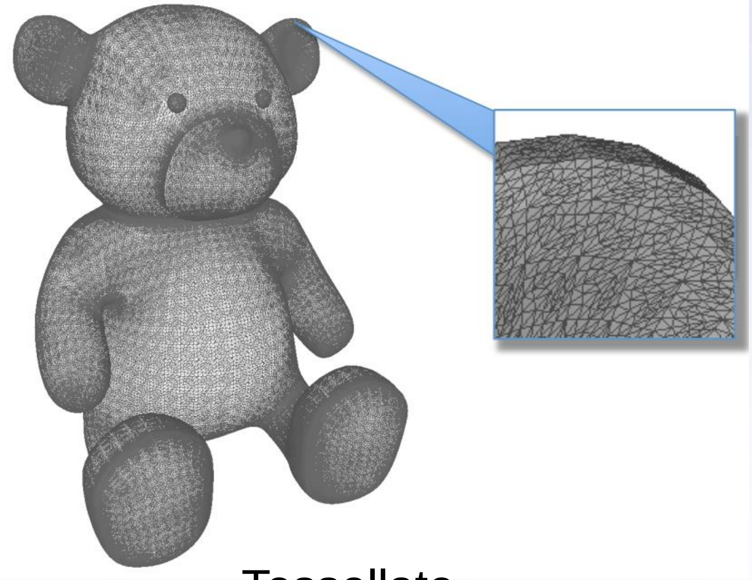
- **Material design – how to fabricate**
  - **The OpenFab Programming Model**



To deal with large memory storage and computational cost, use pipeline (similar to streaming), that is “Not process all at one time”. Key – Local computation



Input



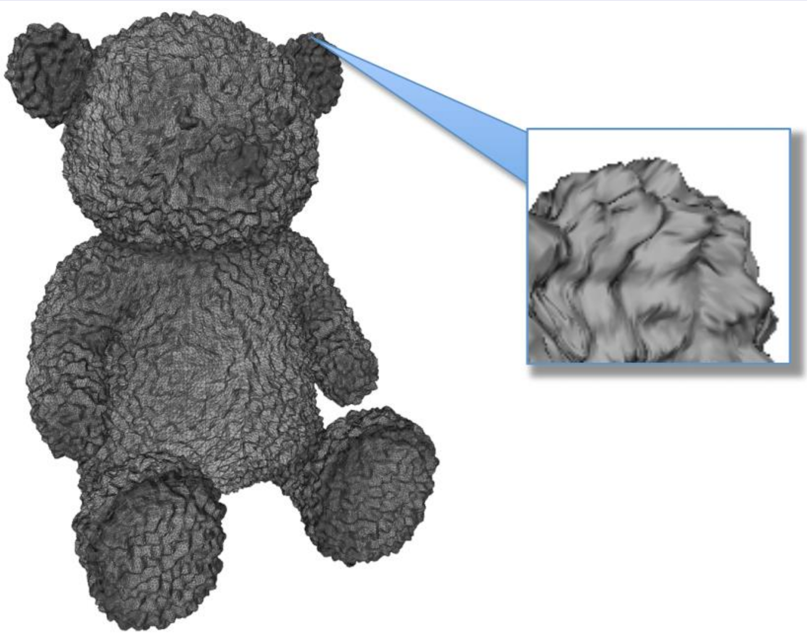
Tessellate

Vidimče, Kiril, et al. "OpenFab: A programmable pipeline for multi-material fabrication." *ACM Transactions on Graphics (TOG)* 32.4 (2013): 136.

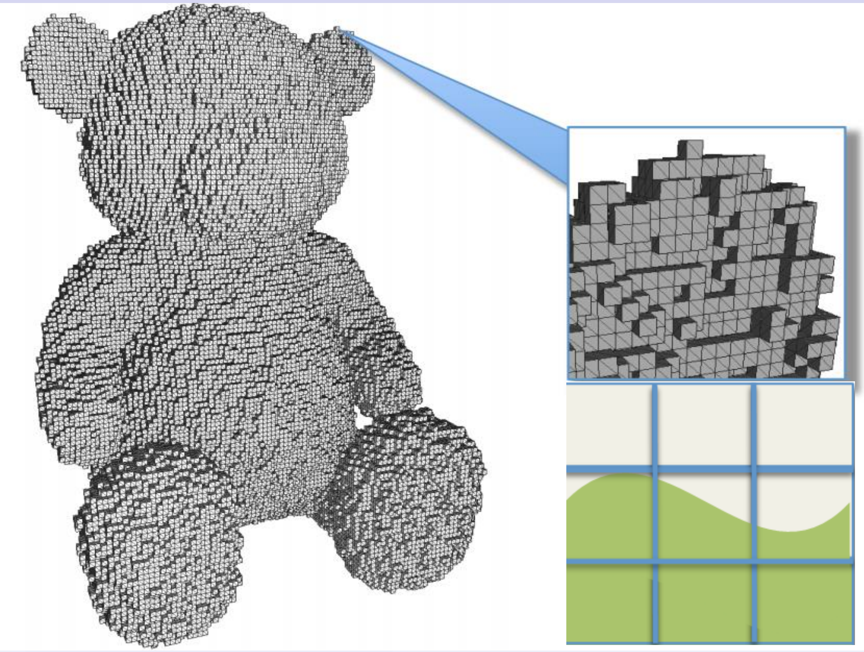
Design
Optimization
Geometry
Materials

Design for AM

- **Material design – how to fabricate**
  - **The OpenFab Programming Model**



Surface stage: allow inputs (e.g., texture)

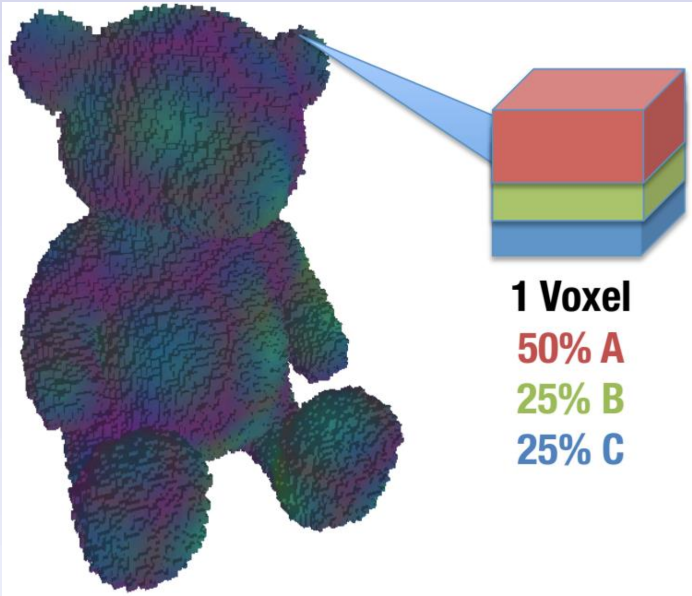


Voxelization

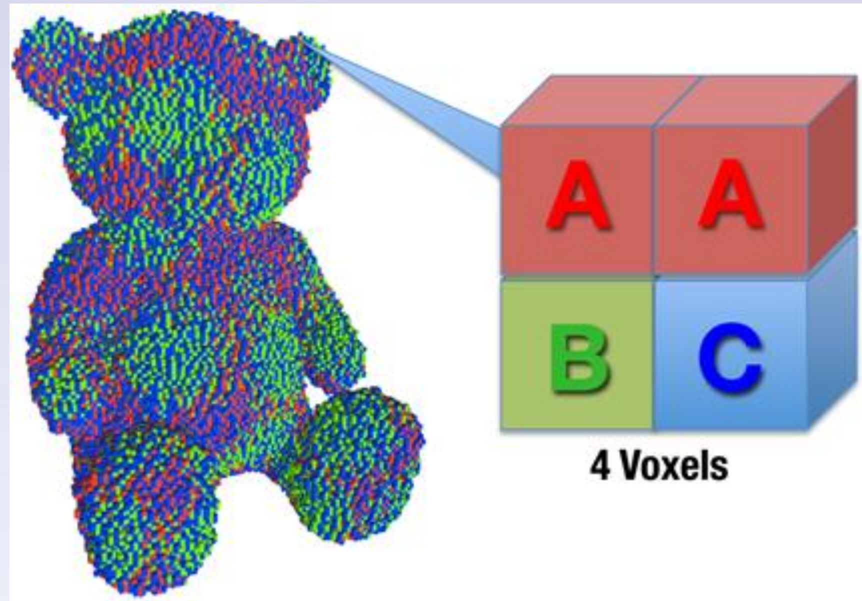
Vidimče, Kiril, et al. "OpenFab: A programmable pipeline for multi-material fabrication." *ACM Transactions on Graphics (TOG)* 32.4 (2013): 136.

Design for AM

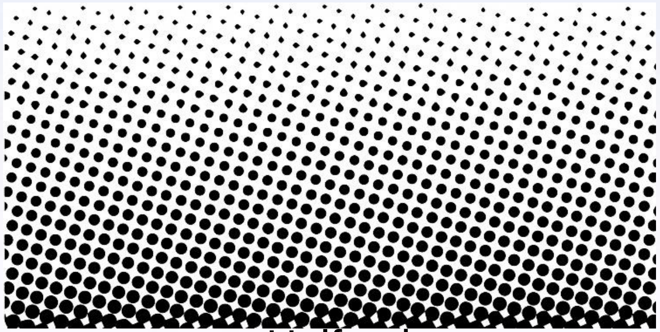
- **Material design – how to fabricate**
  - **The OpenFab Programming Model**



Volume stage: allow inputs (e.g., materials)



Dither

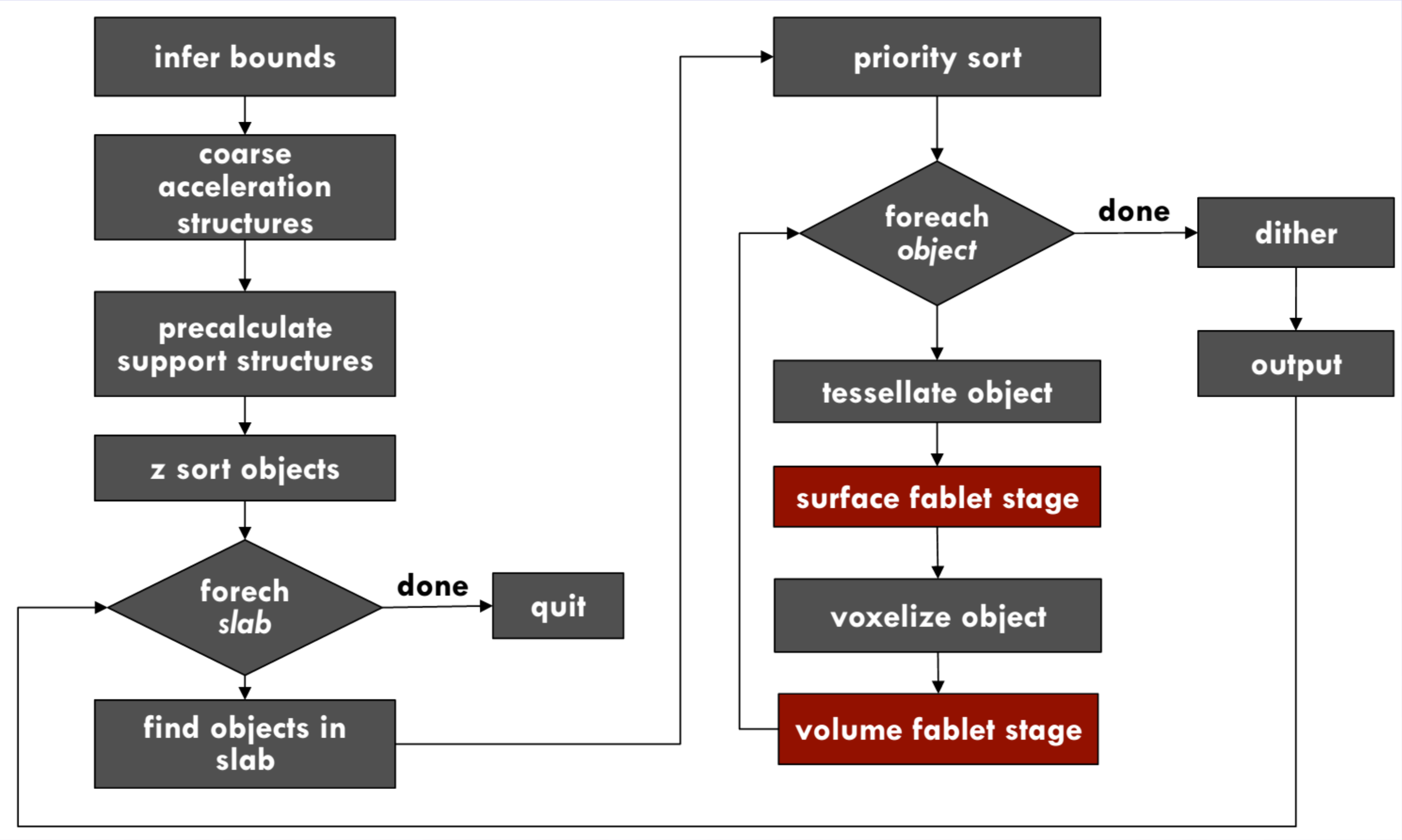


Halftoning

Vidimče, Kiril, et al. "OpenFab: A programmable pipeline for multi-material fabrication." *ACM Transactions on Graphics (TOG)* 32.4 (2013): 136.

Design for AM

- **Material design – how to fabricate**
  - **The OpenFab Programming Model**



Vidimče, Kiril, et al. "OpenFab: A programmable pipeline for multi-material fabrication." *ACM Transactions on Graphics (TOG)* 32.4 (2013): 136.

Design for AM

- **Material design**

One material part

Opportunities

- **How to automate design and optimization structures with multiple materials for non-natural properties**
- **How to evaluate complex multi-material structure (multiphase, interface modeling)**
- **How to add multi-material functionality to 3D printer (i.e., model with material information and generate machine instructions with material information)**
- **How to add more functionality to the structure using multiple materials**


THANK
YOU!