Computational Fabrication

COS 426: Computer Graphics

Szymon Rusinkiewicz

PRINCETON UNIVERSITY

Slide credits: Amit H. Bermano, Wojciech Matusik, David Levin


The Economist
Europe loses the mobile-phone war
Africa's new wealth
Japan's tea party
How to switch off the internet
The shoe-thrower's index
Economist.com
Print me a Stradivarius
The manufacturing technology that will change the world
This violin was made using an EOS laser-sintering 3D printer (and it plays beautifully)
c't magazin für computer technik
€ 3,90
11
Räumlich scannen mit Kamera oder Kinect
Kopieren in 3D
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Die große CPU-Übersicht
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REVIEWS
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THE DESIGN ISSUE
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WIRED
THIS MACHINE WILL CHANGE THE WORLD
This man [MAKERBOT'S BRE PETTIS] will show you how.
Print amazing objects at home!
THE NEW REPLICATOR 3-D PRINTER

The Economist The third industrial revolution

The Economist

APRIL 21ST–27TH 2012

Economist.com

Romneyomics explained

The euro crisis: back after its siesta

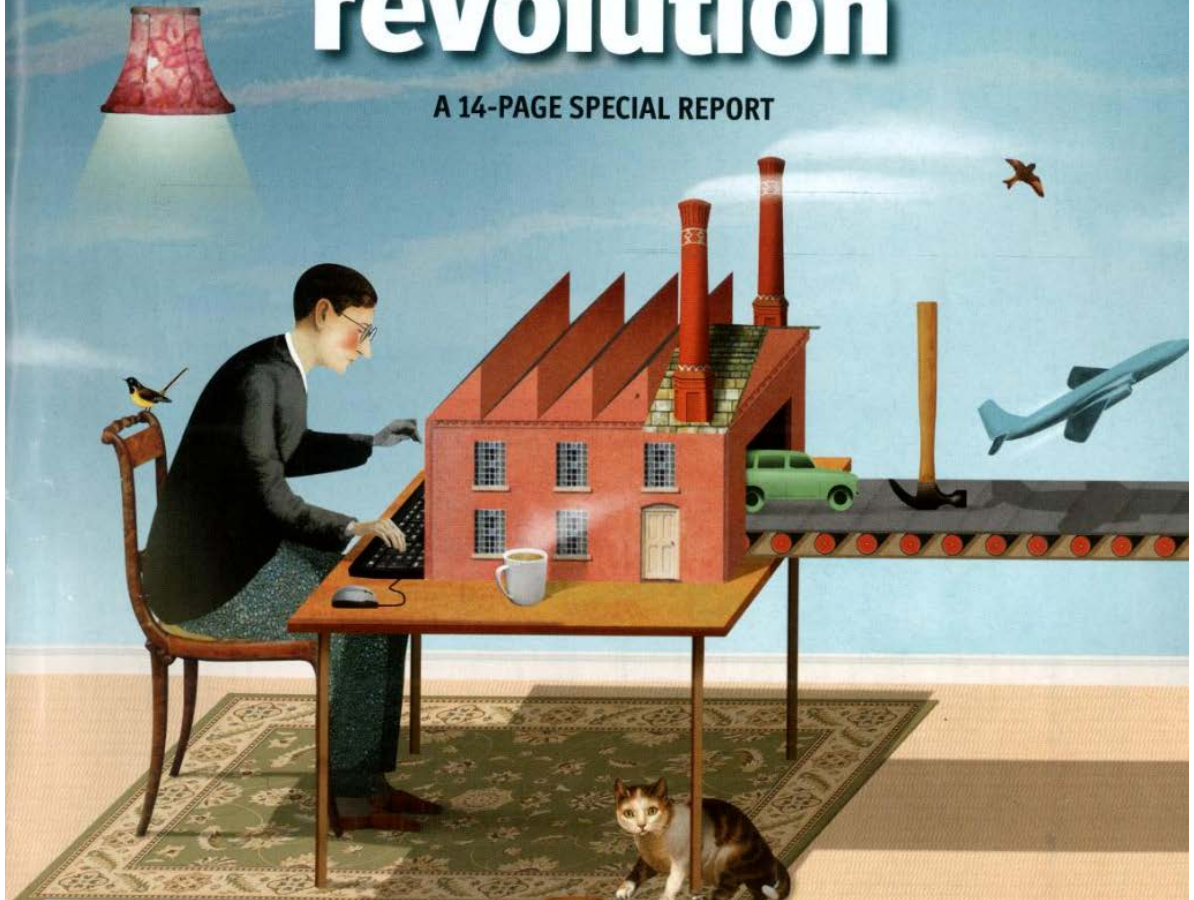
Argentina's oil grab

The science of guerrilla warfare

America's bagel king

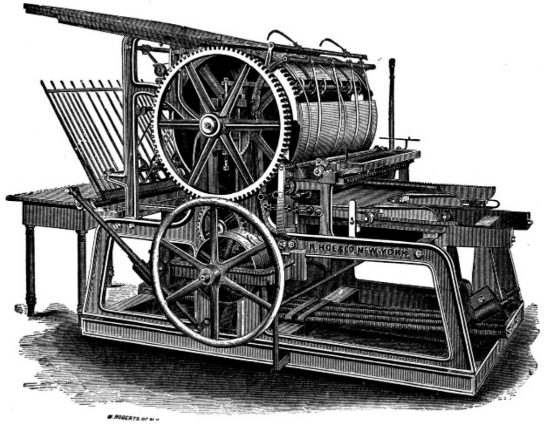
The third industrial revolution

A 14-PAGE SPECIAL REPORT



£4.20

The Third Industrial Revolution



The Third Industrial Revolution

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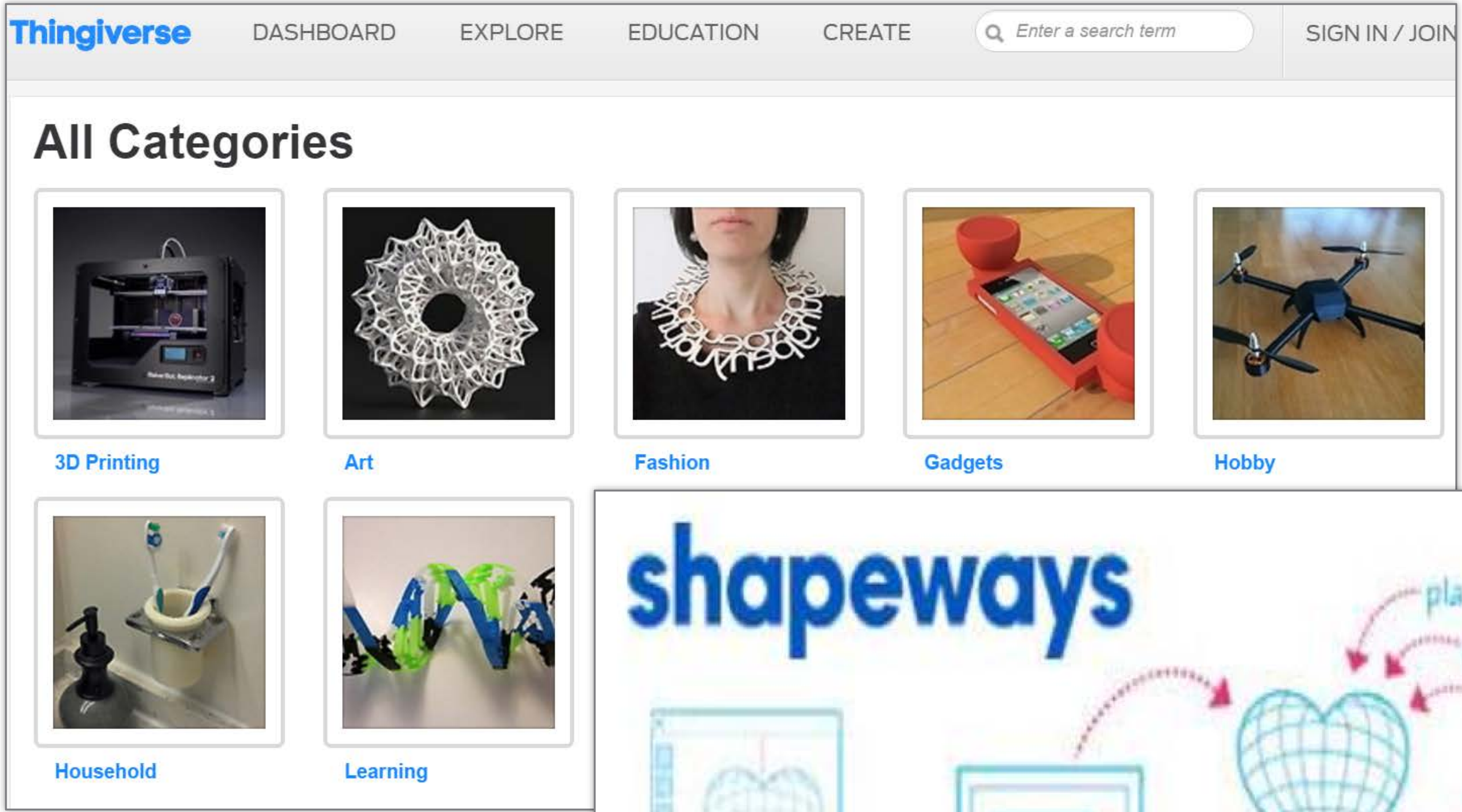

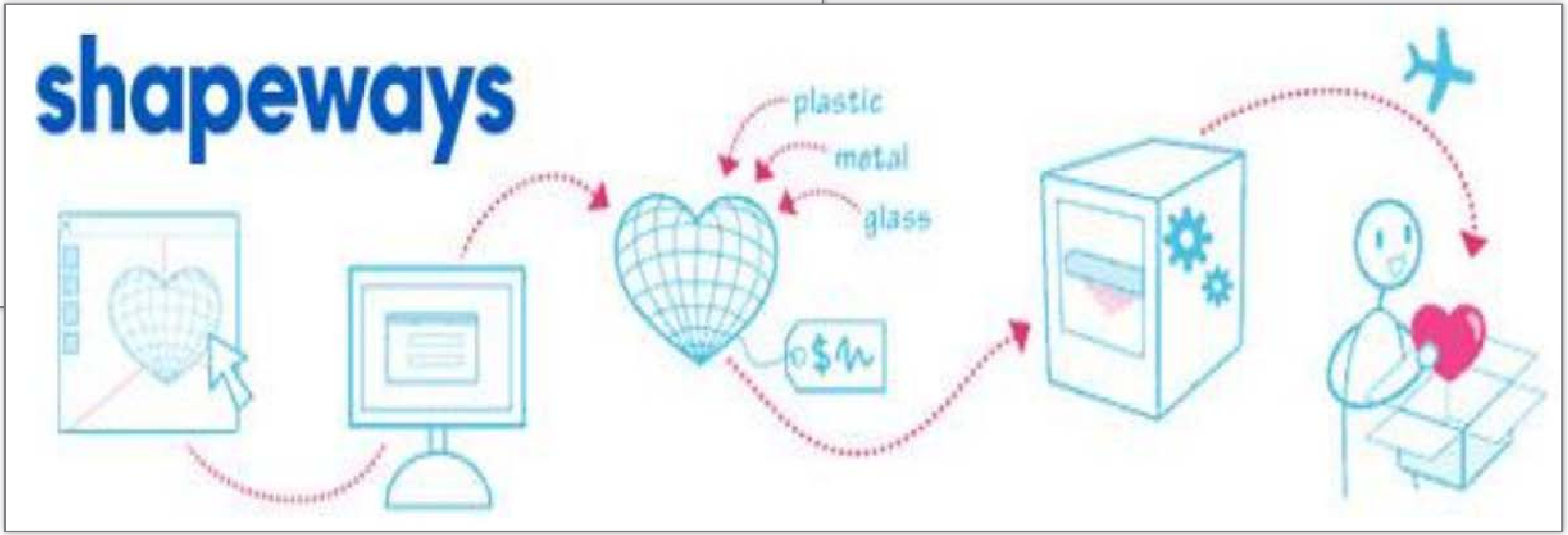

Agenda

- What is additive manufacturing?
- Challenges
- Computational fabrication and graphics?
- Computational fabrication in graphics

Agenda

- **What is additive manufacturing?**
  - **Technologies**
  - **Applications**
- Challenges
- Computational fabrication and graphics?
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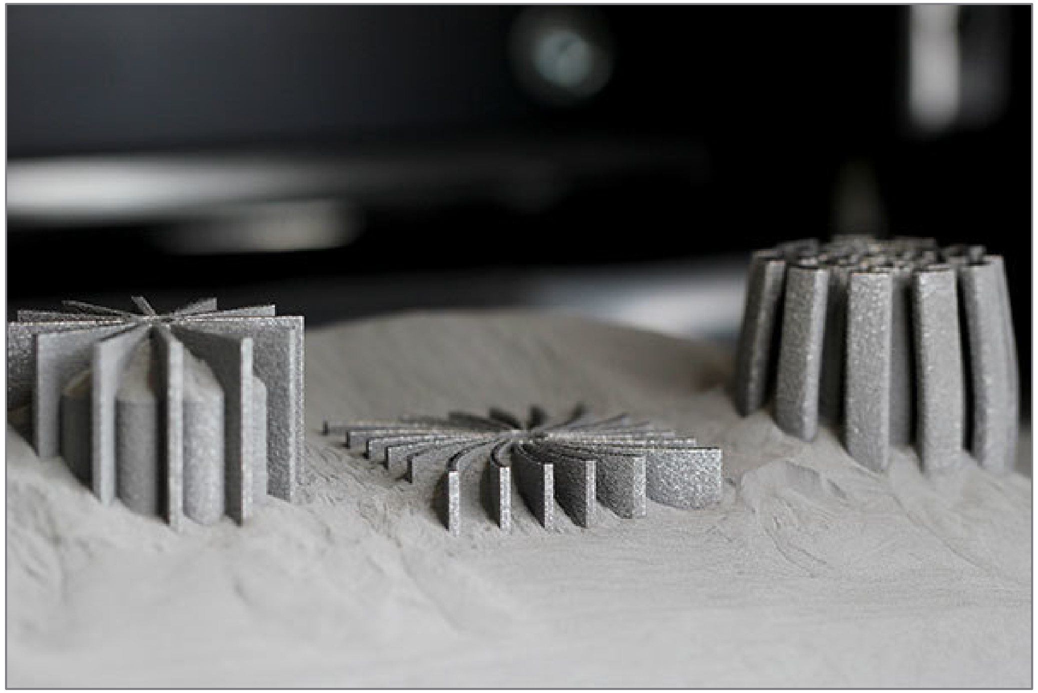
Additive Manufacturing

- Additive vs. Subtractive
  - Most “traditional” manufacturing (e.g. with lathes, mills) is subtractive
- “3D Printing” coined at MIT in 1995



Additive Manufacturing Technologies

- Fused deposition modeling (FDM)
- Stereolithography (SLA)
- Digital Light Projector (DLP) 3D printing
- Selective laser sintering (SLS)
- Direct metal laser sintering (DMLS)
- Plaster-based 3D printing (PP)
- Photopolymer Phase Change Inkjets
- Thermal Phase Change Inkjets
- Laminated object manufacturing (LOM)

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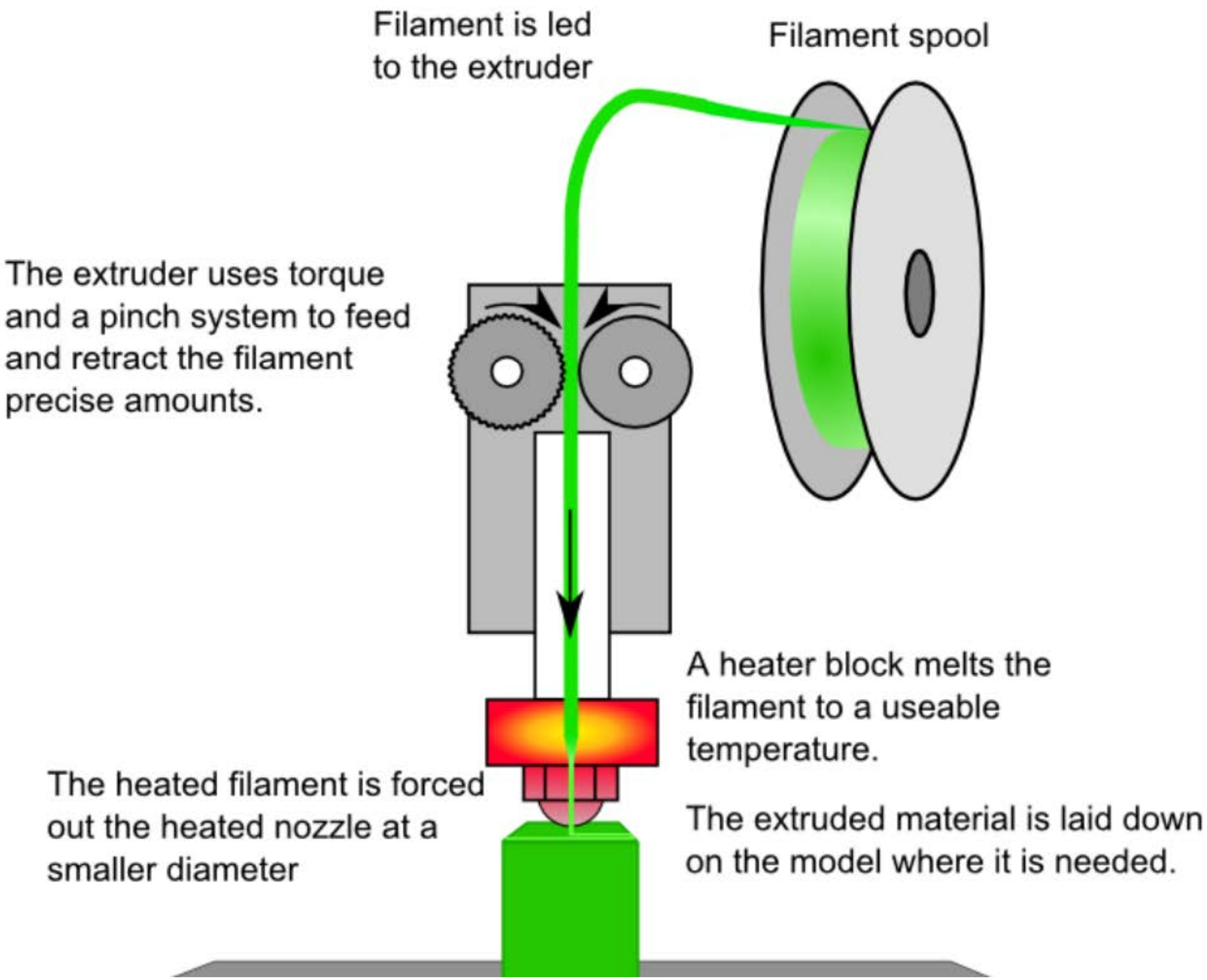

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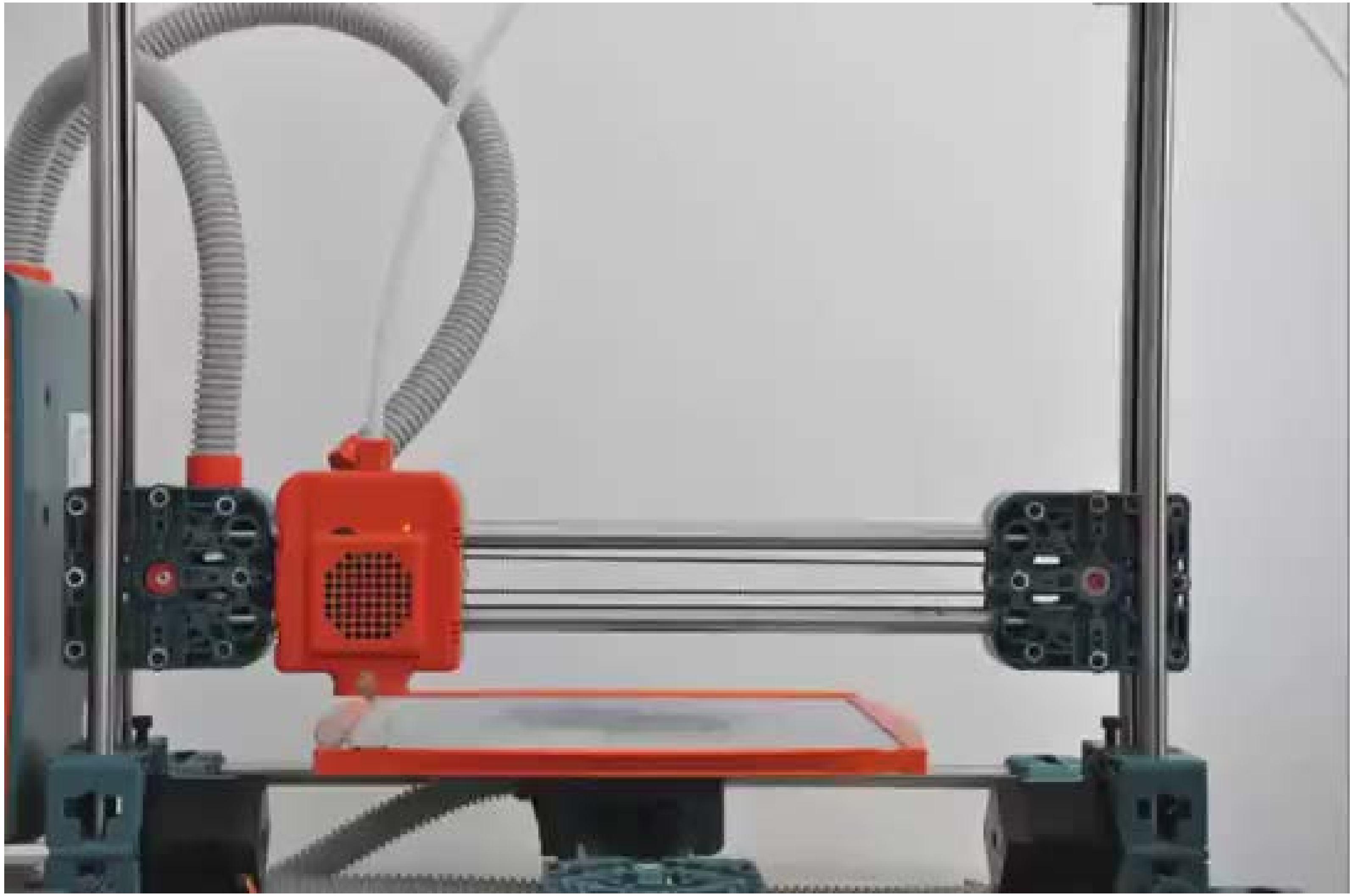

Fused Deposition Modeling (FDM)

OBJET Connex
$250K

MakerBot Replicator 2
~$2K

More units sold per month
than OBJET Connex ever

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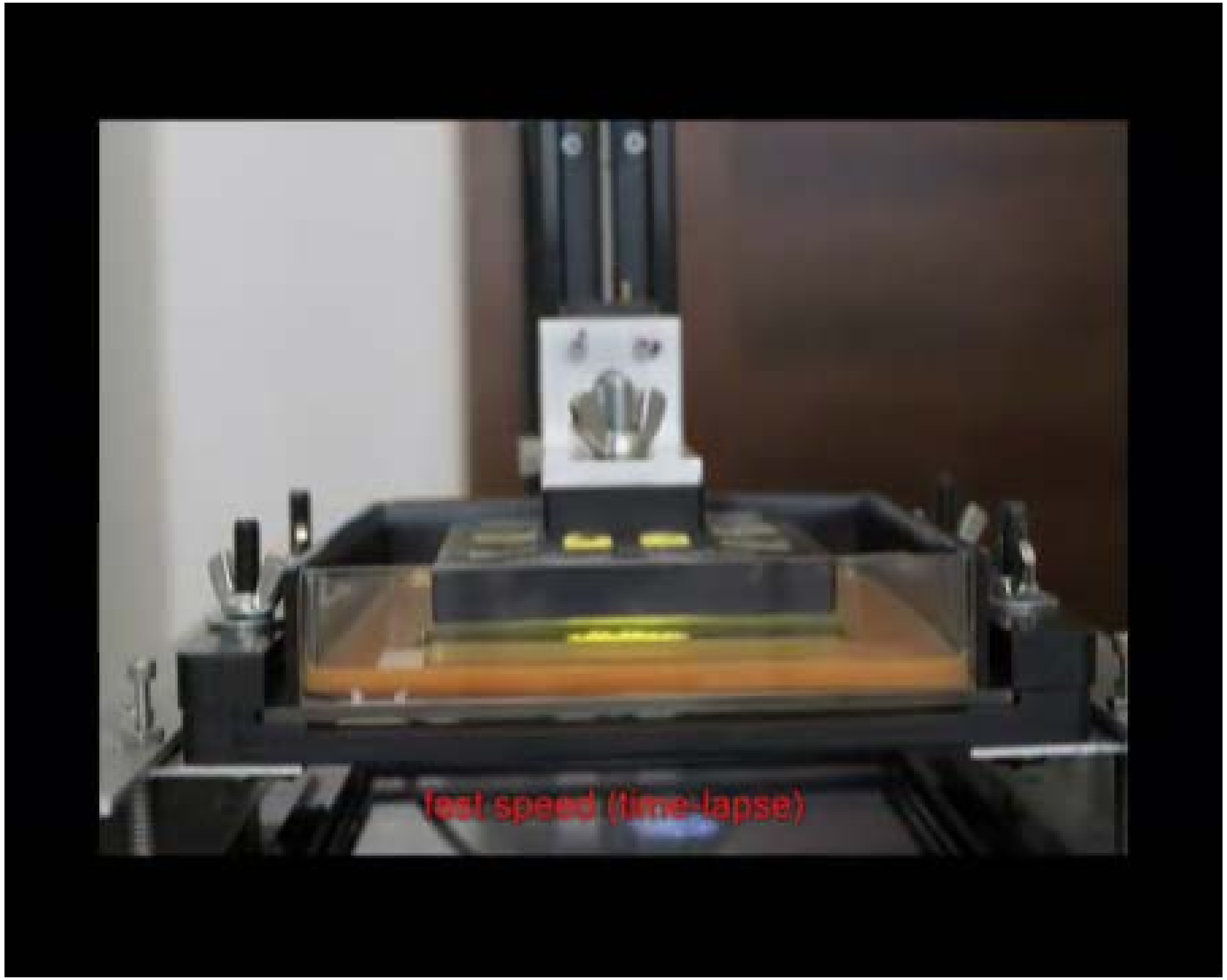
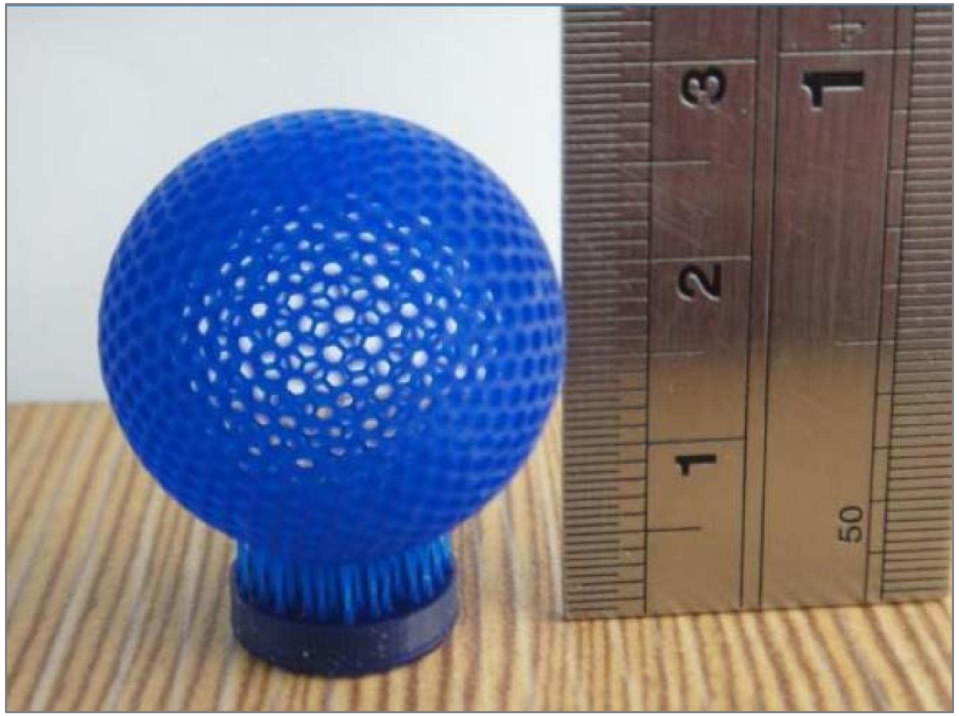
Stereolithography (SLA) & DLP



Stereolithography (SLA) & DLP



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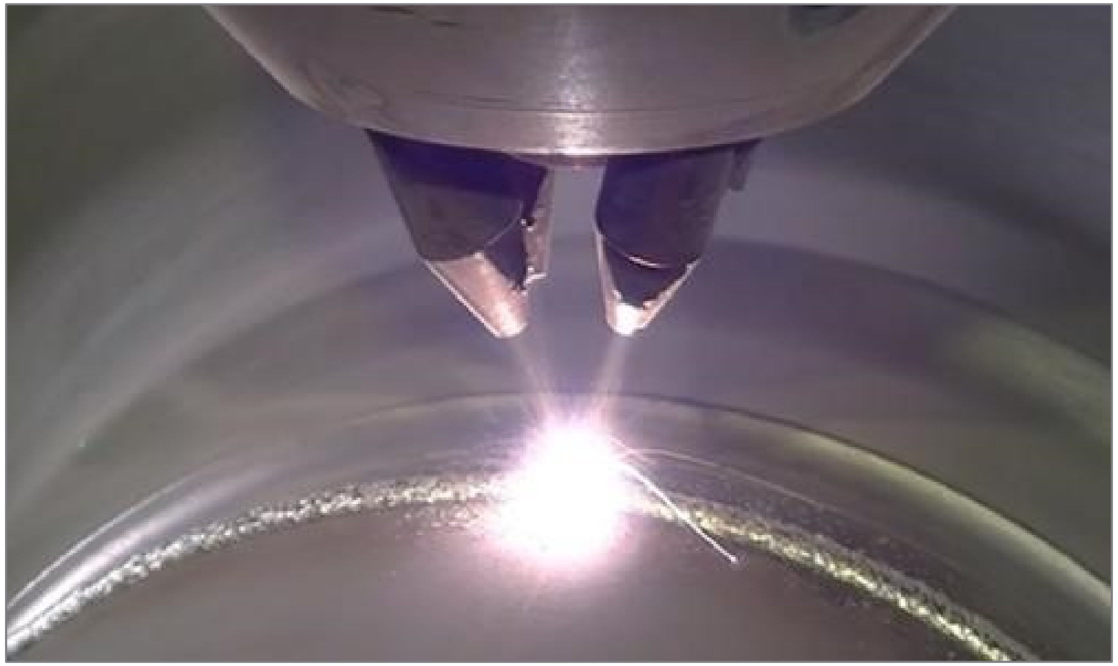
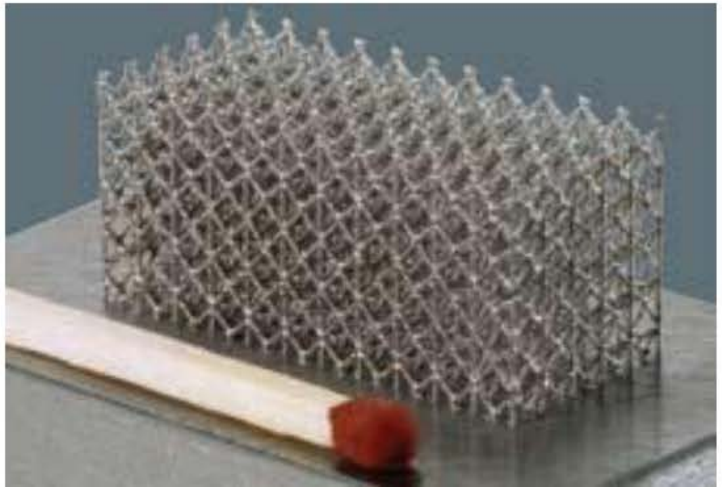
Laser Sintering



Laser Sintering



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Plaster-based 3D printing (PP)

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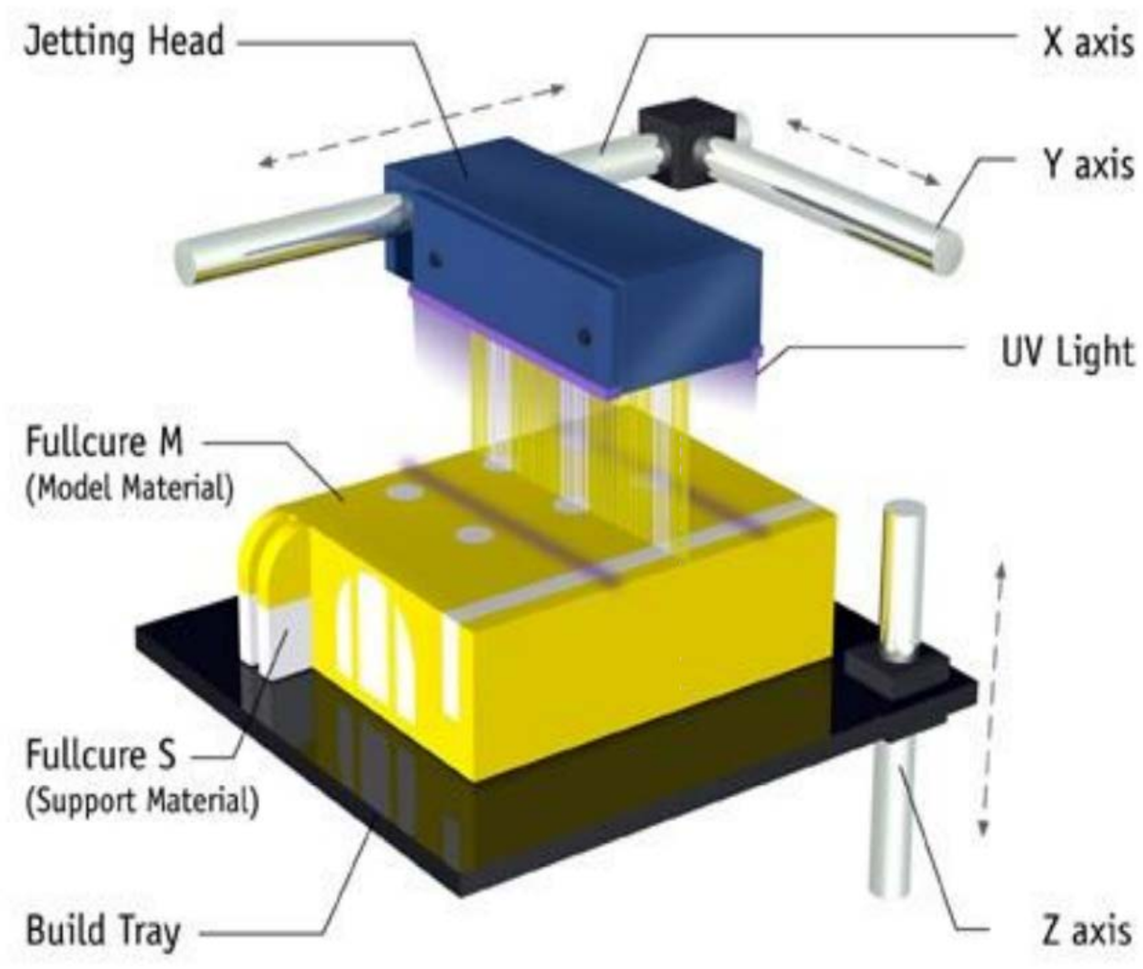
Photopolymer Phase Change Inkjets

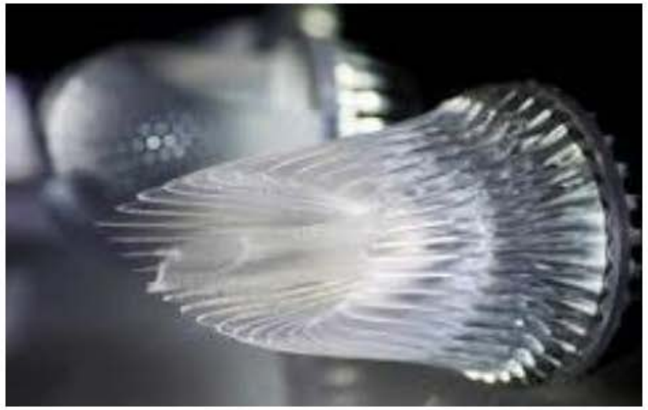


Photopolymer Phase Change Inkjets

Photopolymer Phase Change Inkjets

- Bio-compatible
- High-temperature
- ABS-like
- Transparent
- Opaque
- Rigid
- Rubber-like

Photopolymer Phase Change Inkjets



Exotic Technologies

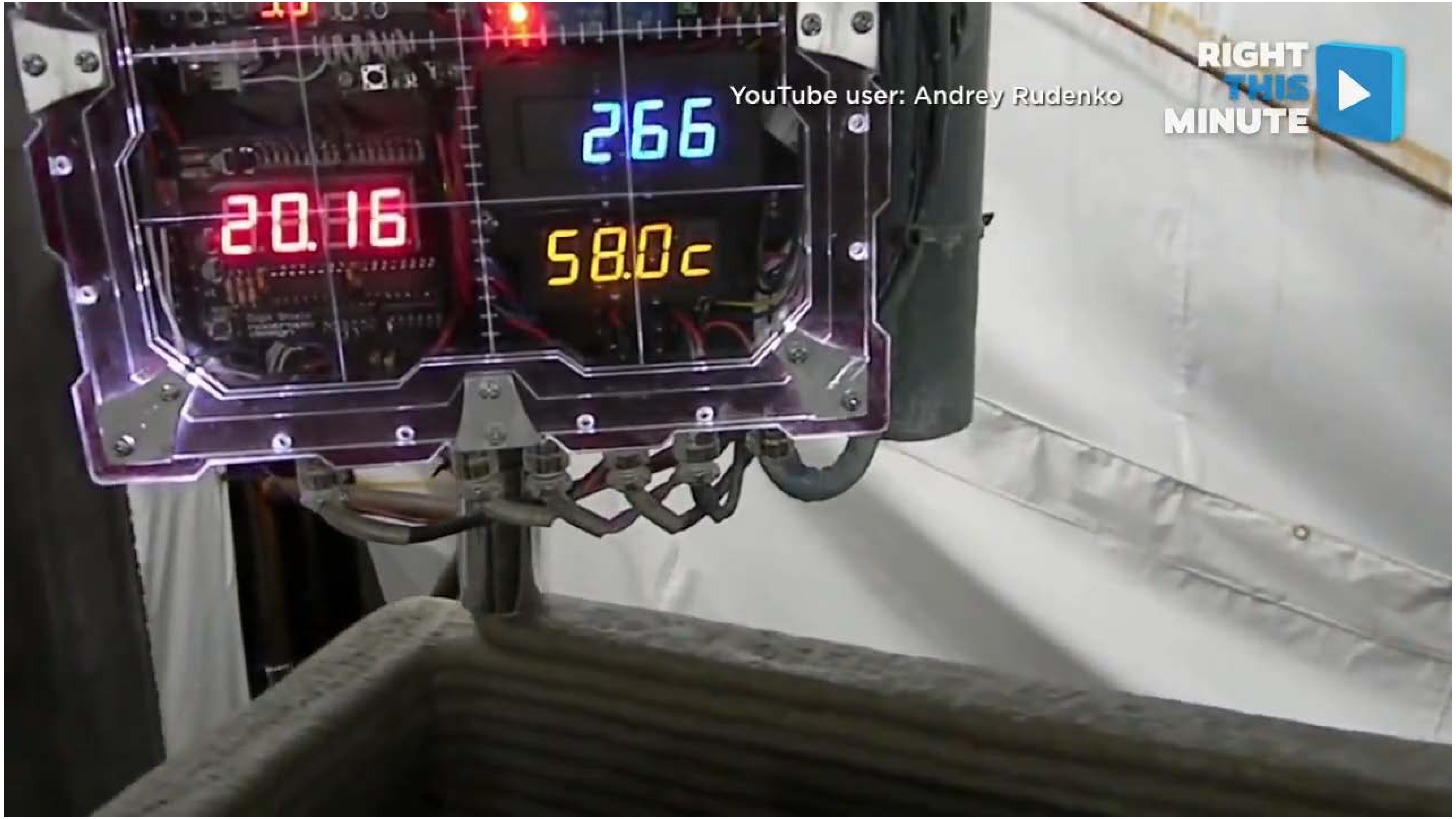
- Food

Exotic Technologies

- Food
- 3D Pens

Exotic Technologies

- Food
- 3D Pens
- Construction



Applications

- Jewelry
- Dental and Medical
- Footwear
- Architecture, Engineering and Construction
- Aerospace
- Automotive
- Consumer Home Products
- Toys and Gadgets
- Art
- Education

Applications

- Jewelry (direct metal printing and casting patterns)






Applications

- Dental and Medical Industries

Crowns, copings, bridges

Custom Hearing Aids

Implants

Prosthetics

Applications

- Footwear




Applications

- Architecture

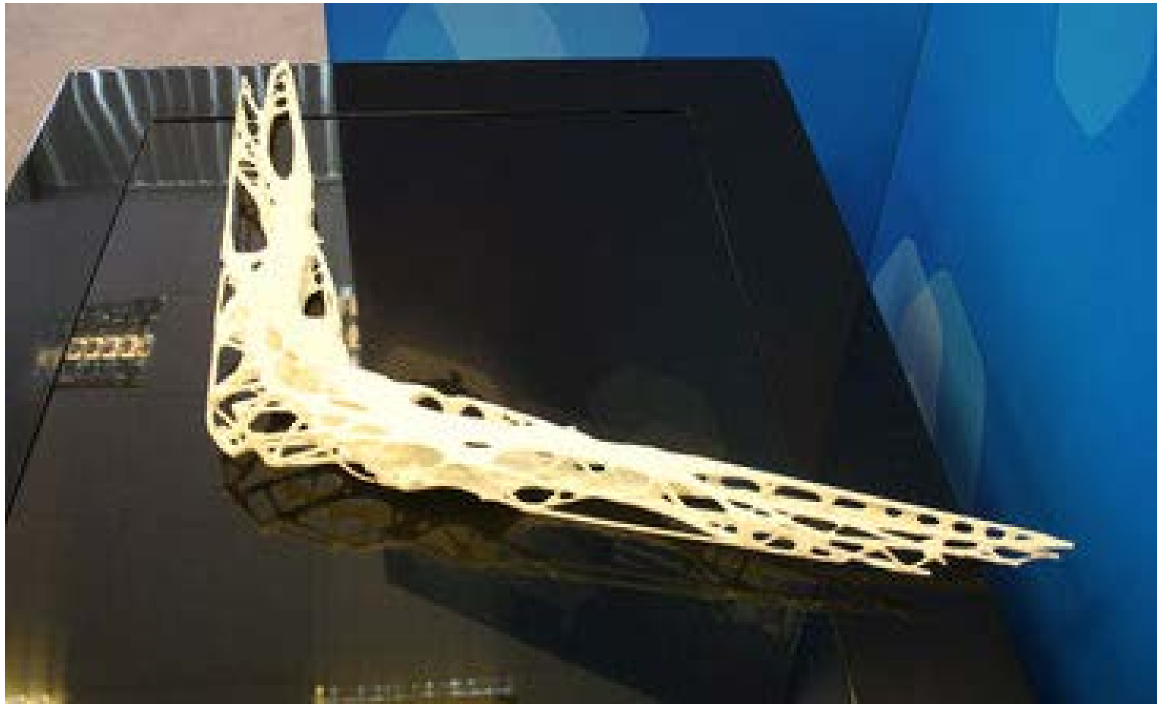
Models

Molds

Applications

- Aerospace

Airbus wing brackets



Bird skeleton inspired wing structures

Applications

- Automotive

Honeycomb Tires

3D Printed Ventilation Prototype
(High Temperature 3D Printing Material)

Applications

- Consumer Home Products

Lamp

Egg cup

Espresso Cup

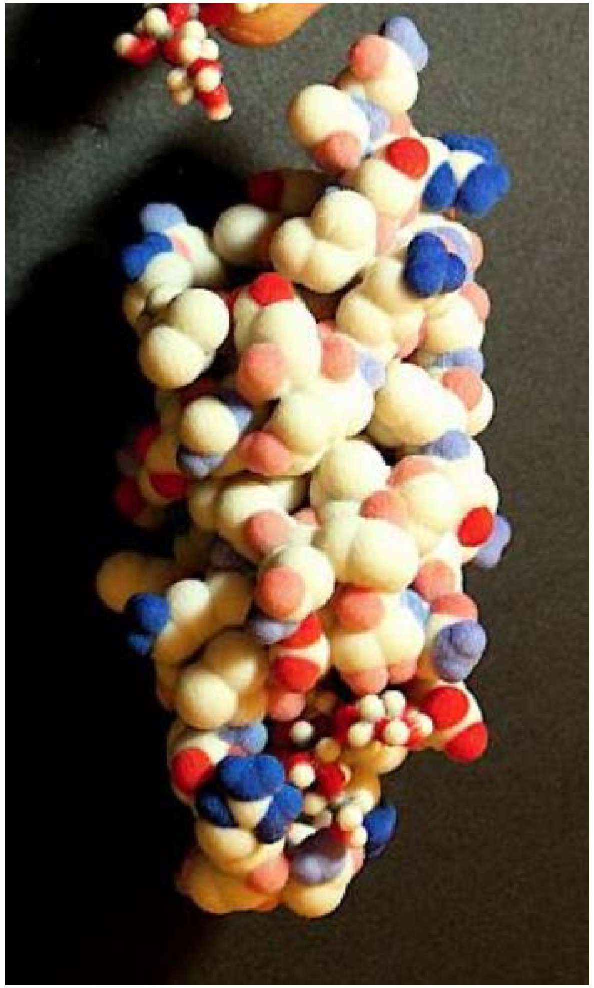
Platter

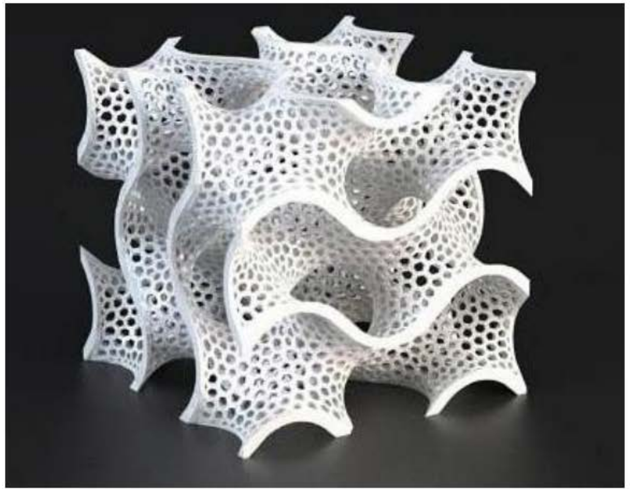
Pencil bowl

Source: Shapeway

Applications

- Toys, Art & Education



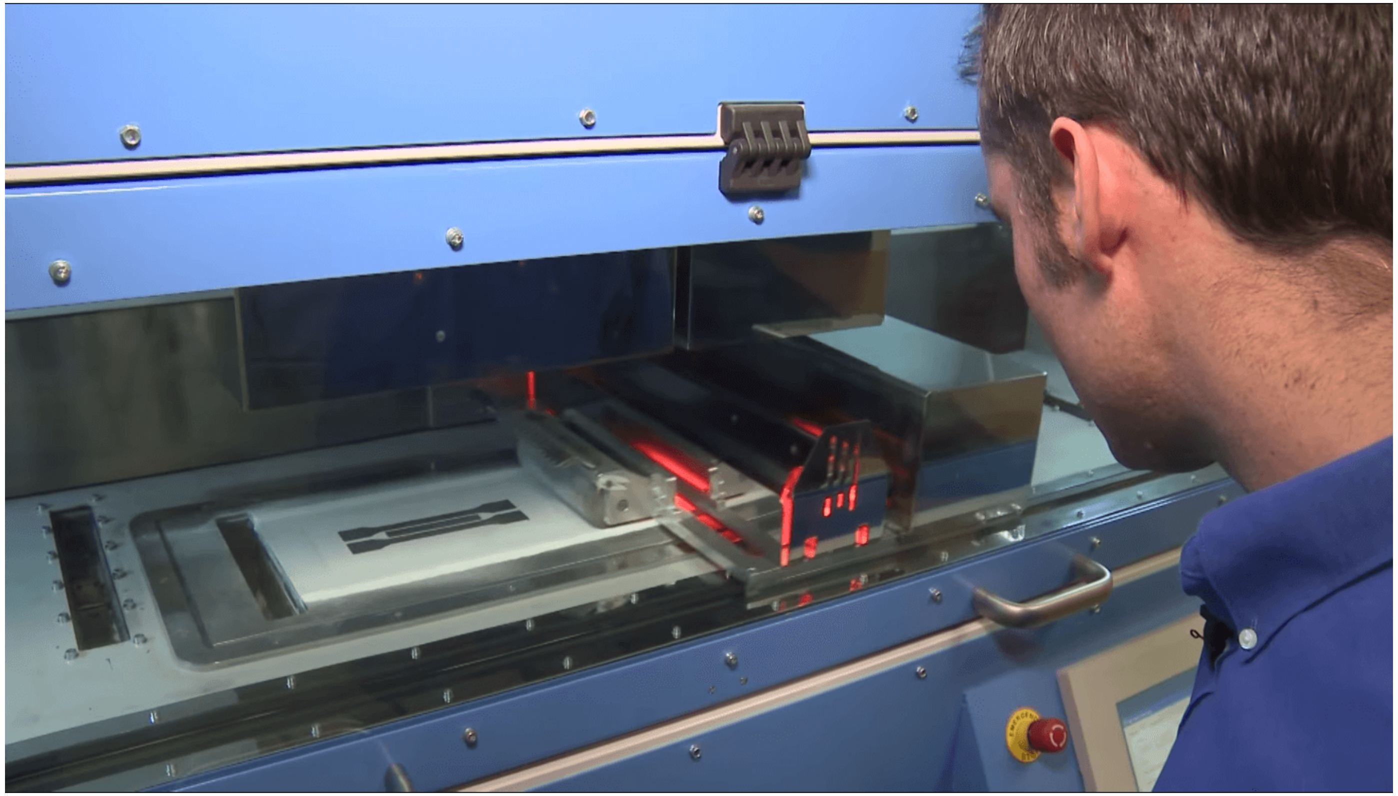


Agenda

- What is additive manufacturing?
- **Challenges**
- Computational fabrication and graphics?
- Computational fabrication in graphics

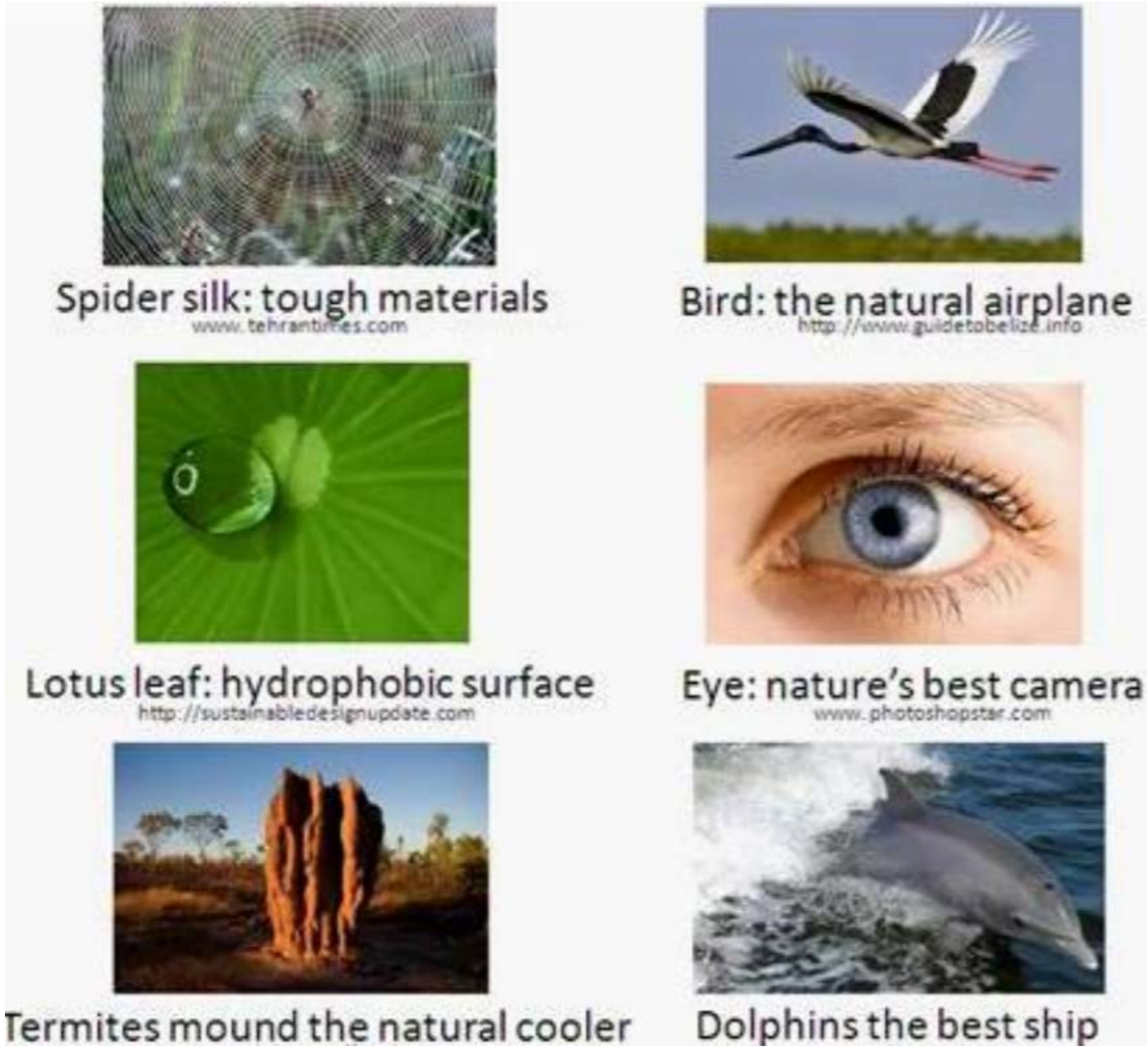
Challenges

- Mechanical + Electrical Engineering Challenges
  - Slow – Printing 5″ x 5″ x 5″ object takes 10+ hours
  - Expensive – $100 / lb
  - Print Volume



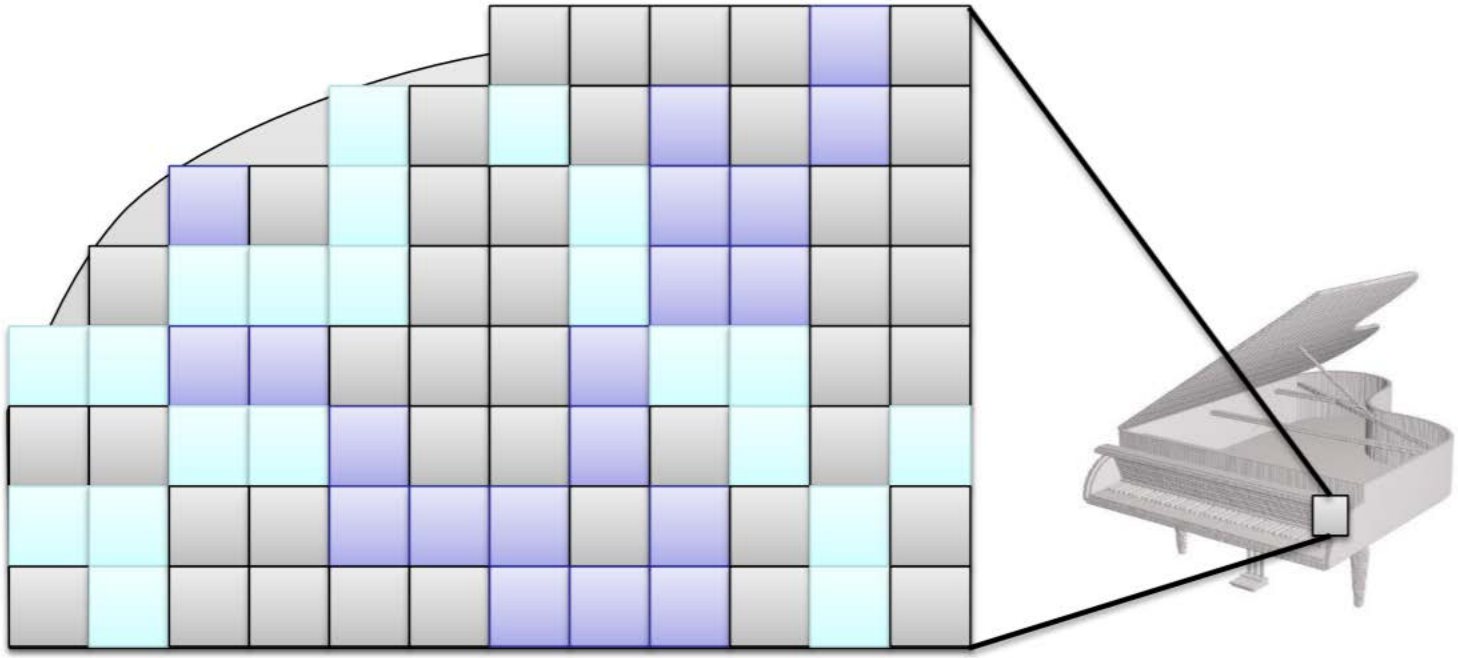
Challenges

- Material Challenges
  - Physical properties:
    - Strength / weight
    - Deformability (stretchy, flexible)
    - Magnetism, conductivity
    - Heat resistance and transfer
  - Optical properties:
    - Color
    - Shininess, roughness
    - Translucency
    - BRDF…
  - Interfaces between materials



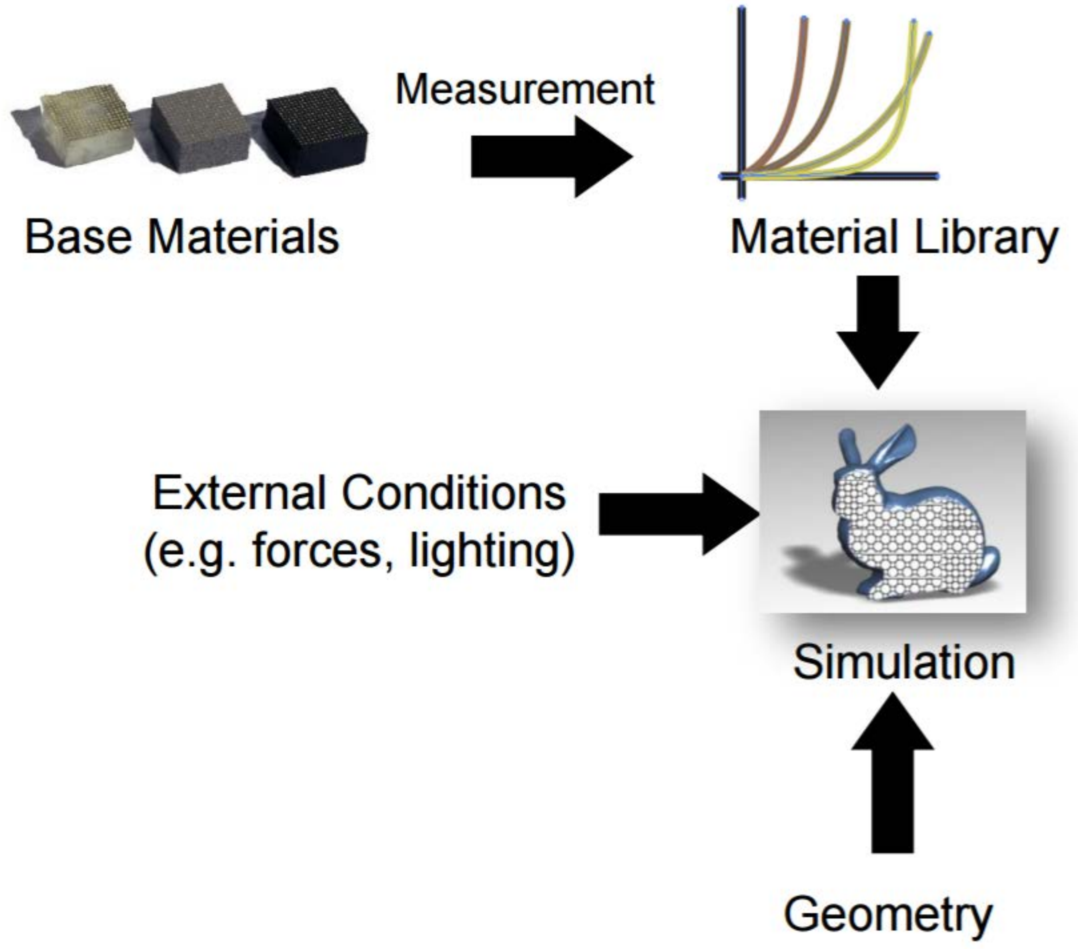
Challenges

- Software Challenges
  - **Data Requirements & Representations:**
    Giga voxels/inch^3 , Tera voxels/foot^3



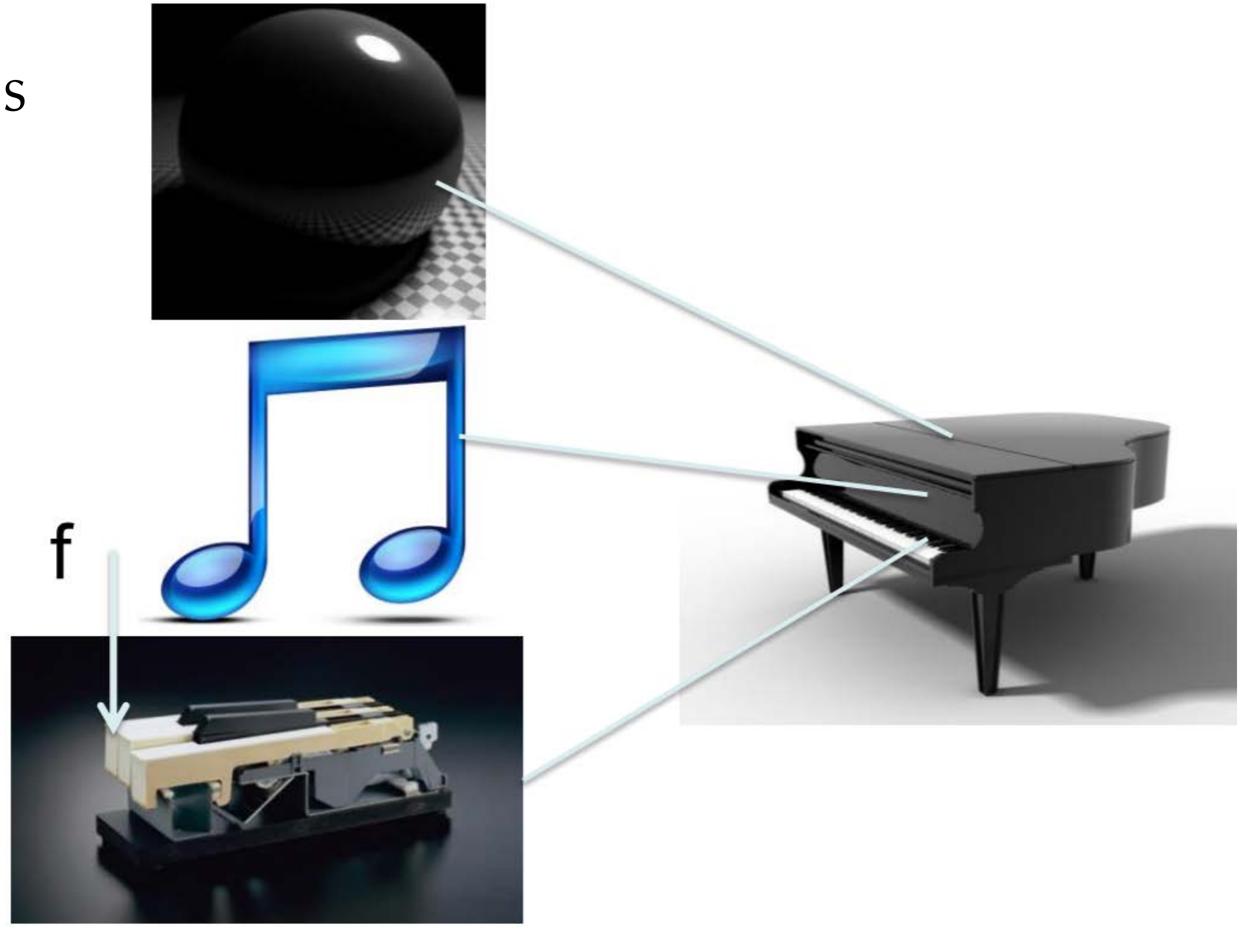
Challenges

- Software Challenges
  - Data Requirements & Representations
  - **Measurement & Simulation**



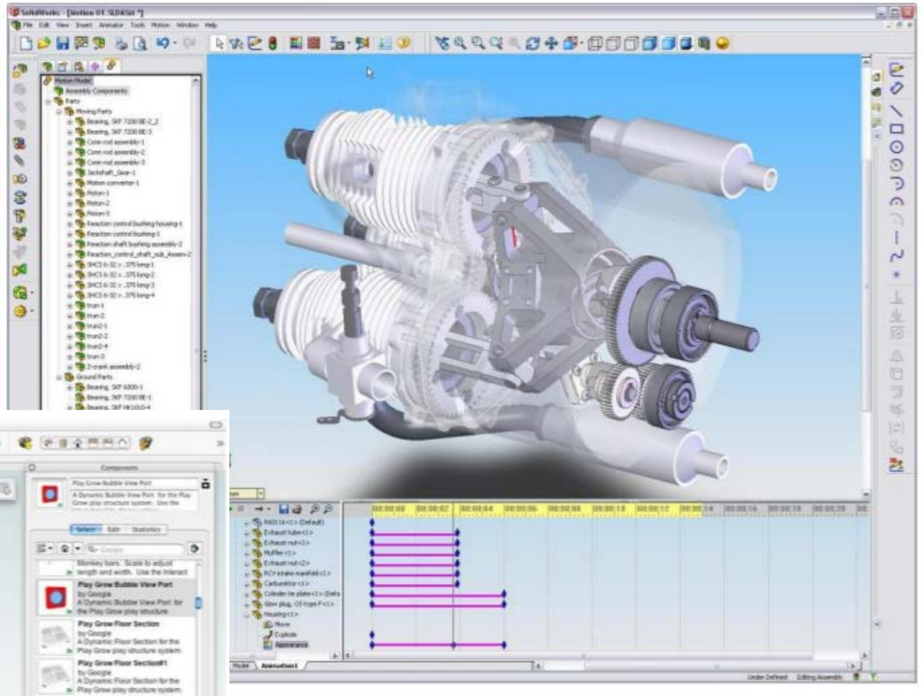
Challenges

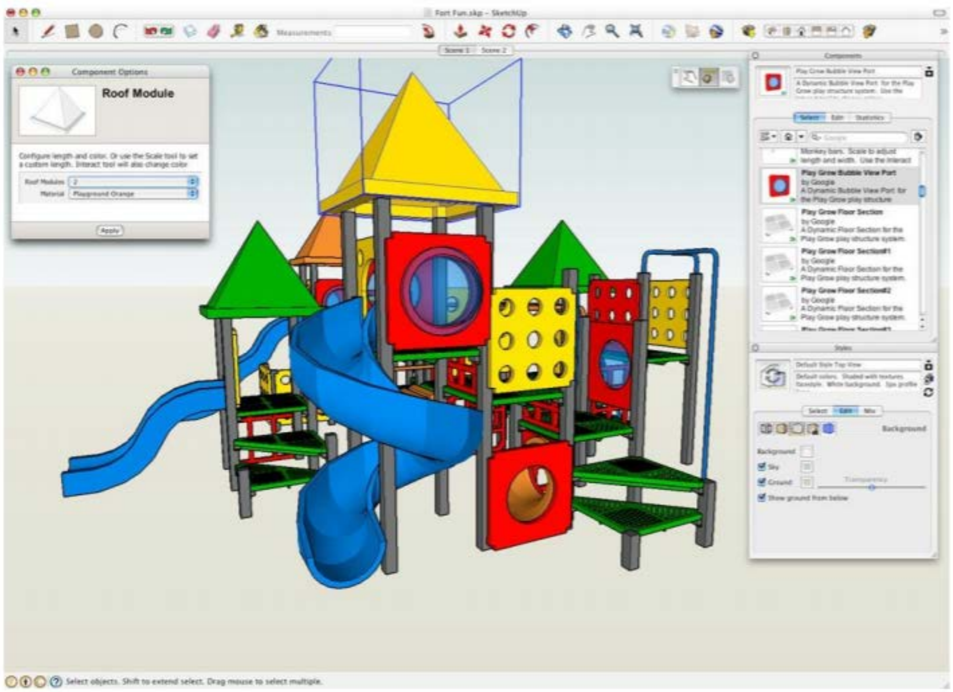
- Software Challenges
  - Data Requirements & Representations
  - Measurement & Simulation
  - **Optimization**



Challenges

- Software Challenges
  - Data Requirements & Representations
  - Measurement & Simulation
  - Optimization
  - **Design tools**





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- What is additive manufacturing?
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- **Computational fabrication and graphics?**
  - **Appearance**
  - Physical simulation
  - Geometry Processing
  - Animation
- Computational fabrication in graphics

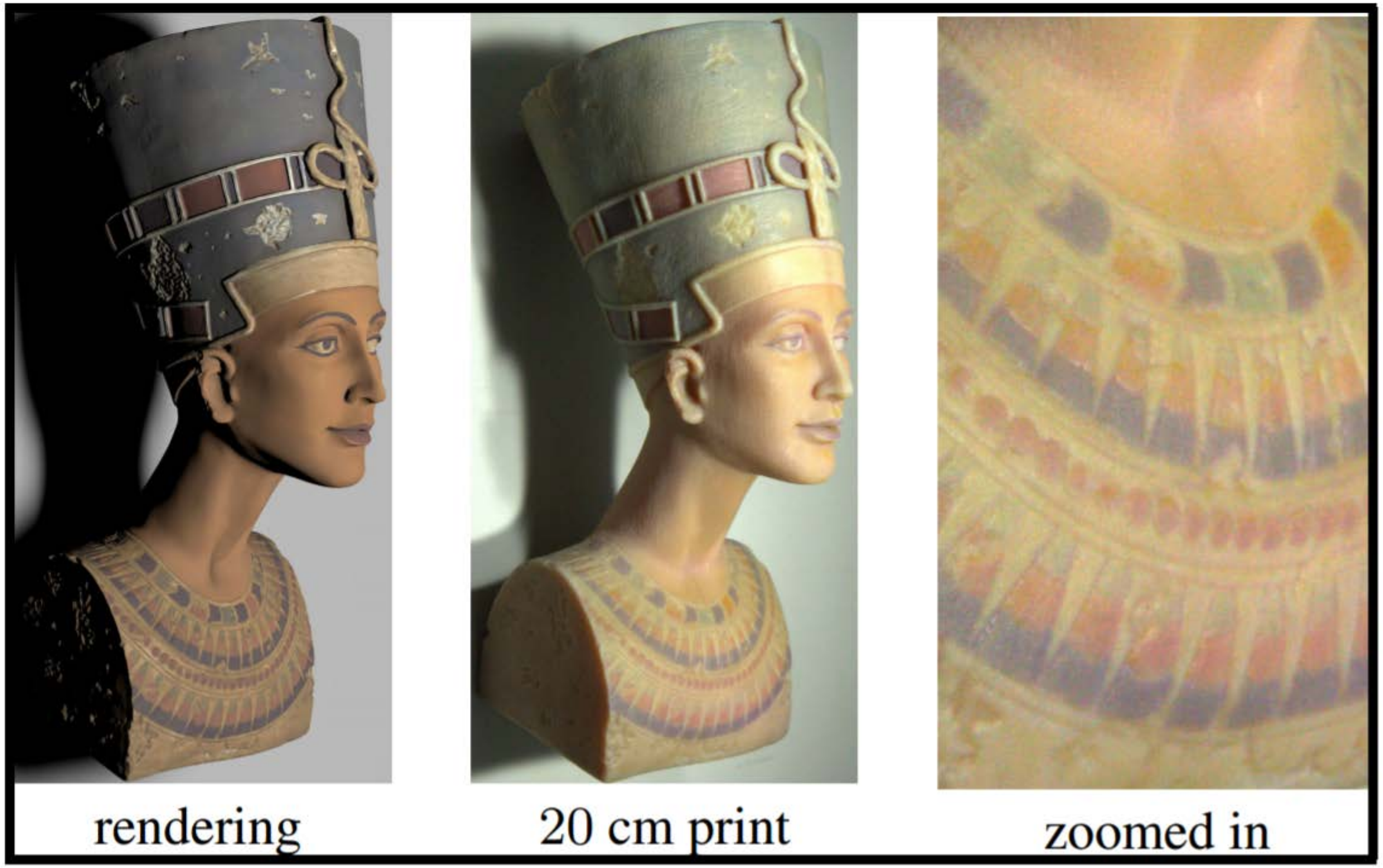
Fabrication and Graphics

- Appearance
  - Halftoning

Dual-Color Mixing for Fused Deposition Modeling Printers [2014]

Fabrication and Graphics

- Appearance
  - Halftoning



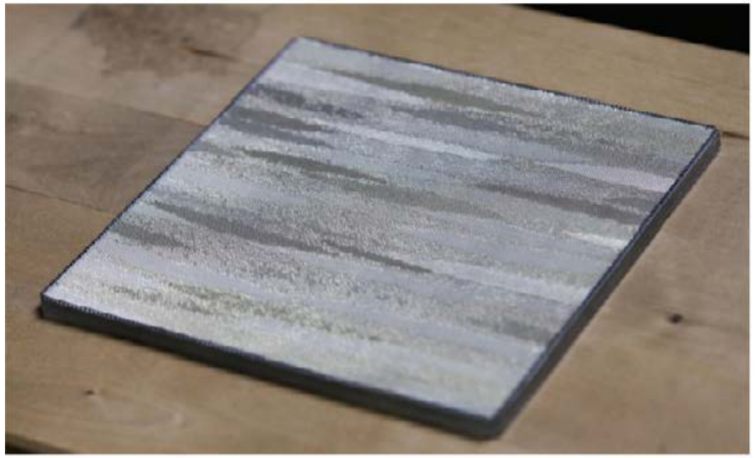
Pushing the Limits of 3D Color Printing: Error diffusion with translucent materials [2015]

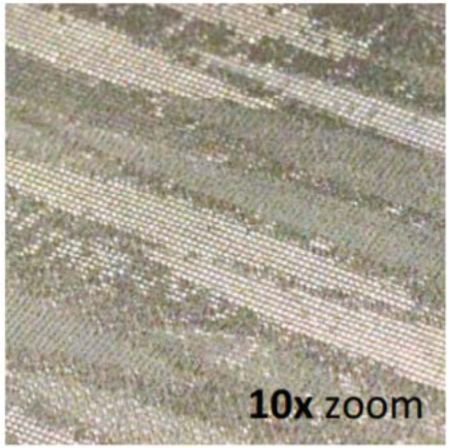
Fabrication and Graphics

- Appearance
  - Halftoning
  - Caustics
  - Reflectance
  - …

ShadowPIX: Multiple Images from Self-Shadowing [2012]

Reliefs as images [2010]





Bi-Scale Appearance Fabrication [2013]

Goal-Based Caustics [2011]

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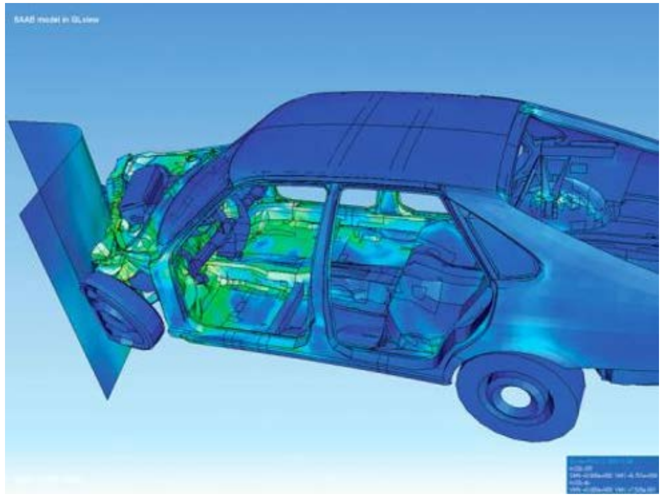
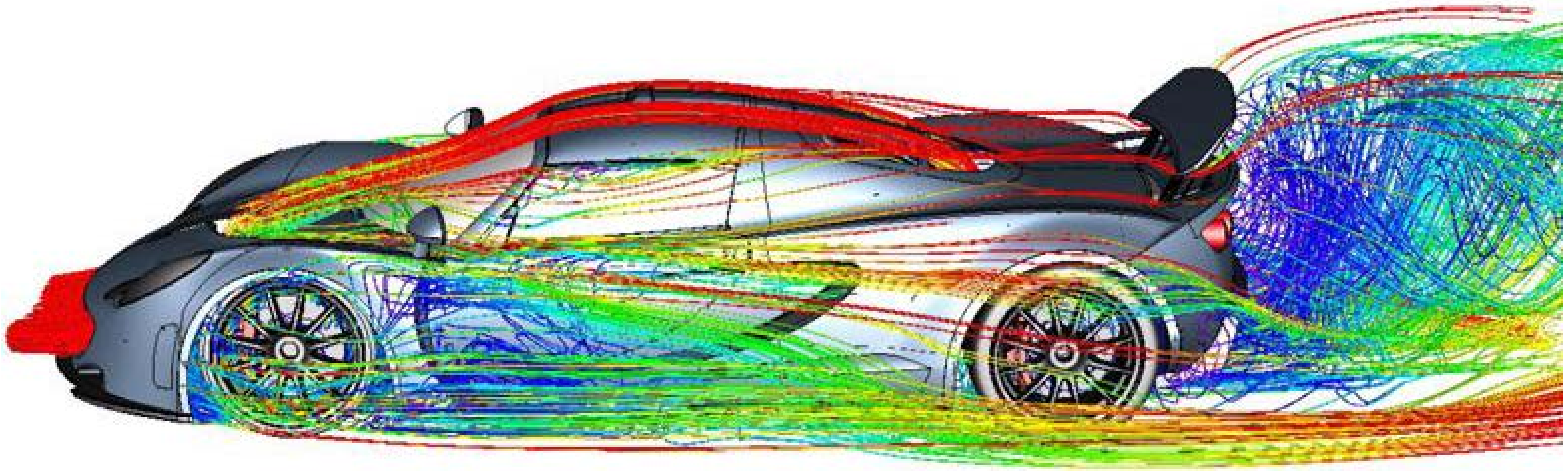
Fabrication and Graphics

- Physically-based simulation
  - Mechanical Engineering
    - **Reproduction** of physical phenomena
    - Predictive capability (accuracy!)
    - Substitute for expensive experiments





Fabrication and Graphics

- Physically-based simulation
  - Mechanical Engineering
    - **Reproduction** of physical phenomena
    - Predictive capability (accuracy!)
    - Substitute for expensive experiments
  - Computer Graphics
    - **Imitation** of physical phenomena
    - Tradeoffs between predictive and merely “visually plausible” behavior
    - Speed, stability, art-directability

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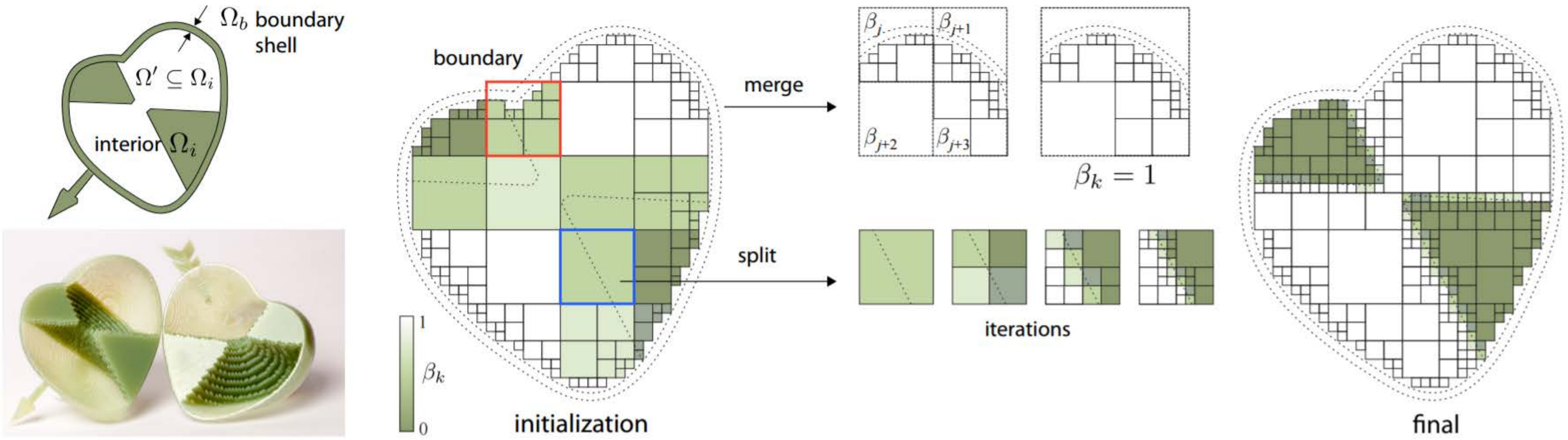
Fabrication and Graphics

- Geometry Processing
  - Efficient representations (e.g., octrees)



Spin-it: Optimizing moment of inertia for spinnable objects [2014]

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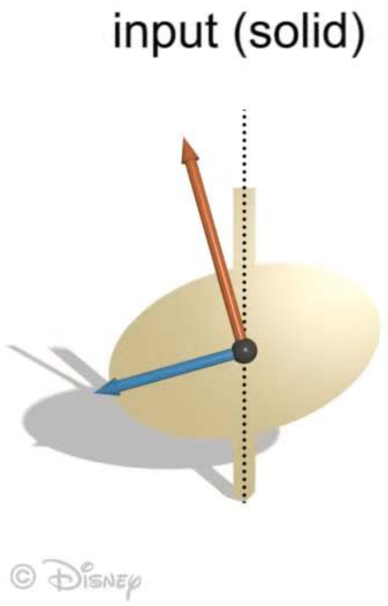
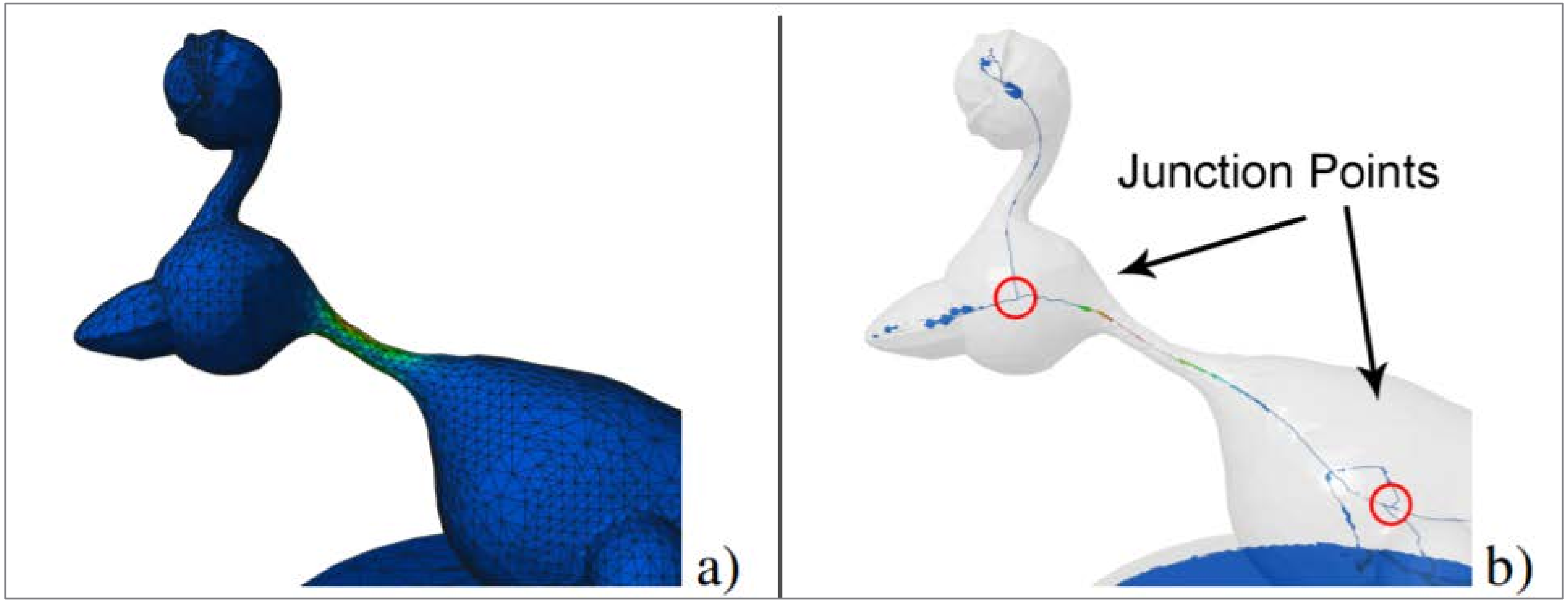


Spin-it: Optimizing moment of inertia for spinnable objects [2014]

Fabrication and Graphics

- Geometry Processing
  - Efficient representations (e.g., octrees)
  - Medial axis



Stress relief: Improving structural strength of 3d printable objects [2012]

Fabrication and Graphics

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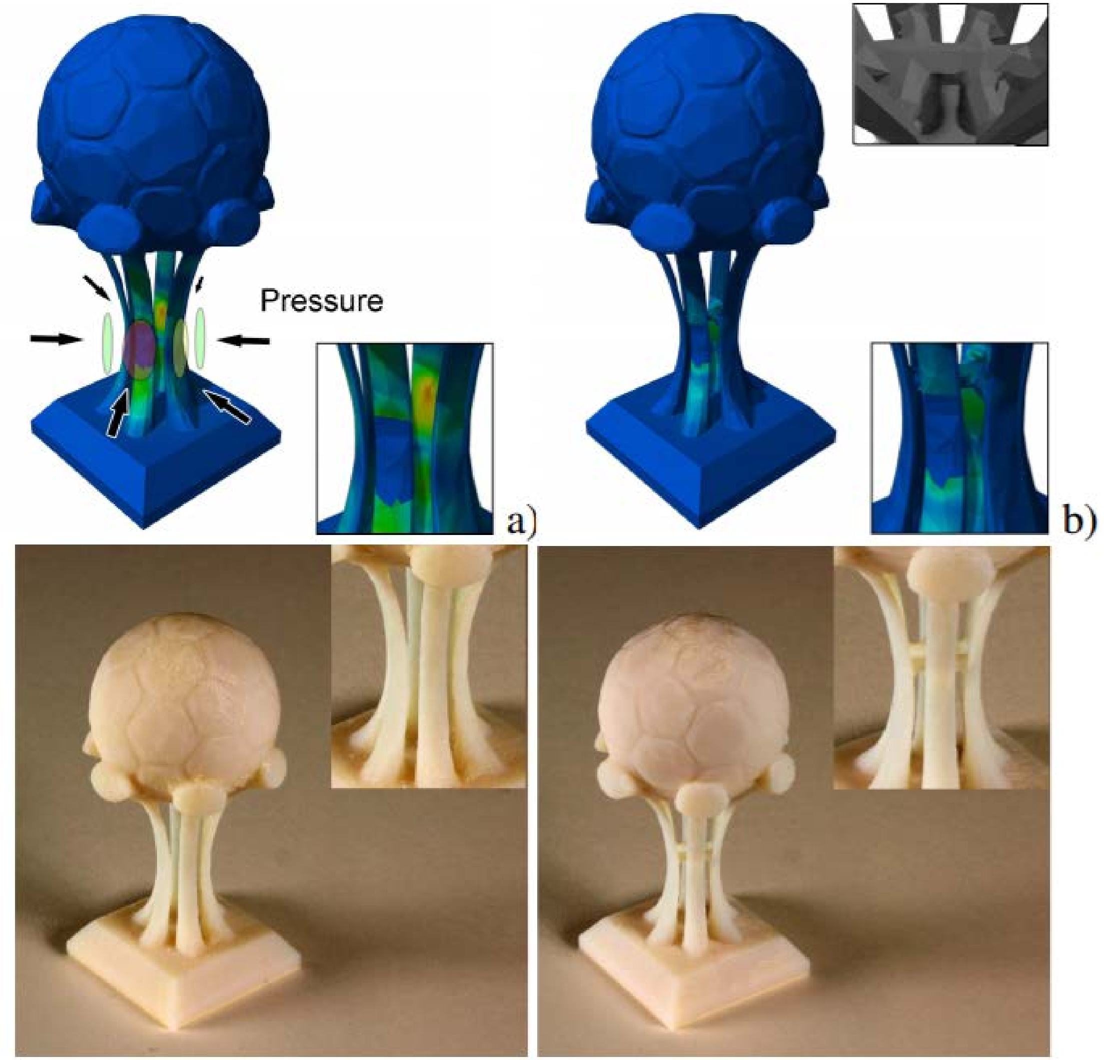
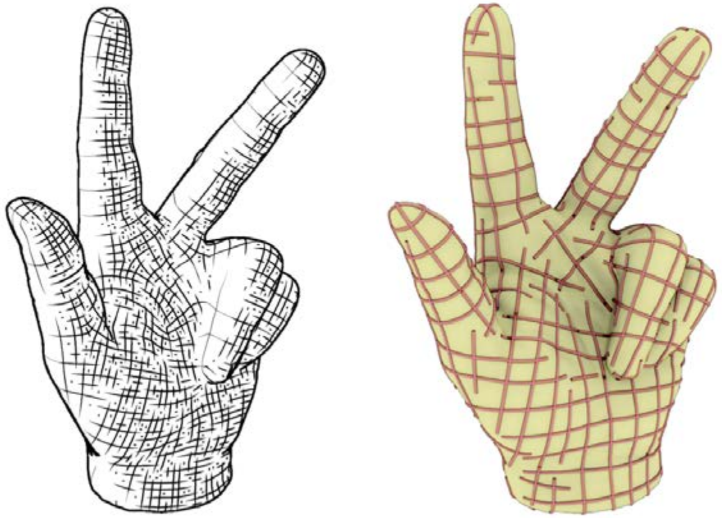


Stress relief: Improving structural strength of 3d printable objects [2012]

Fabrication and Graphics

- Geometry Processing
  - Efficient representations (e.g., octrees)
  - Medial axis
  - Vector field optimization



Field-aligned mesh joinery [2014]

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Fabrication and Graphics

- Animation
  - Rigs
  - Kinematic Chains
  - Motion Capture
  - Motion curves
  - Motion features

Fabricating articulated characters from skinned meshes [2012]

Fabrication and Graphics

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  - Kinematic Chains
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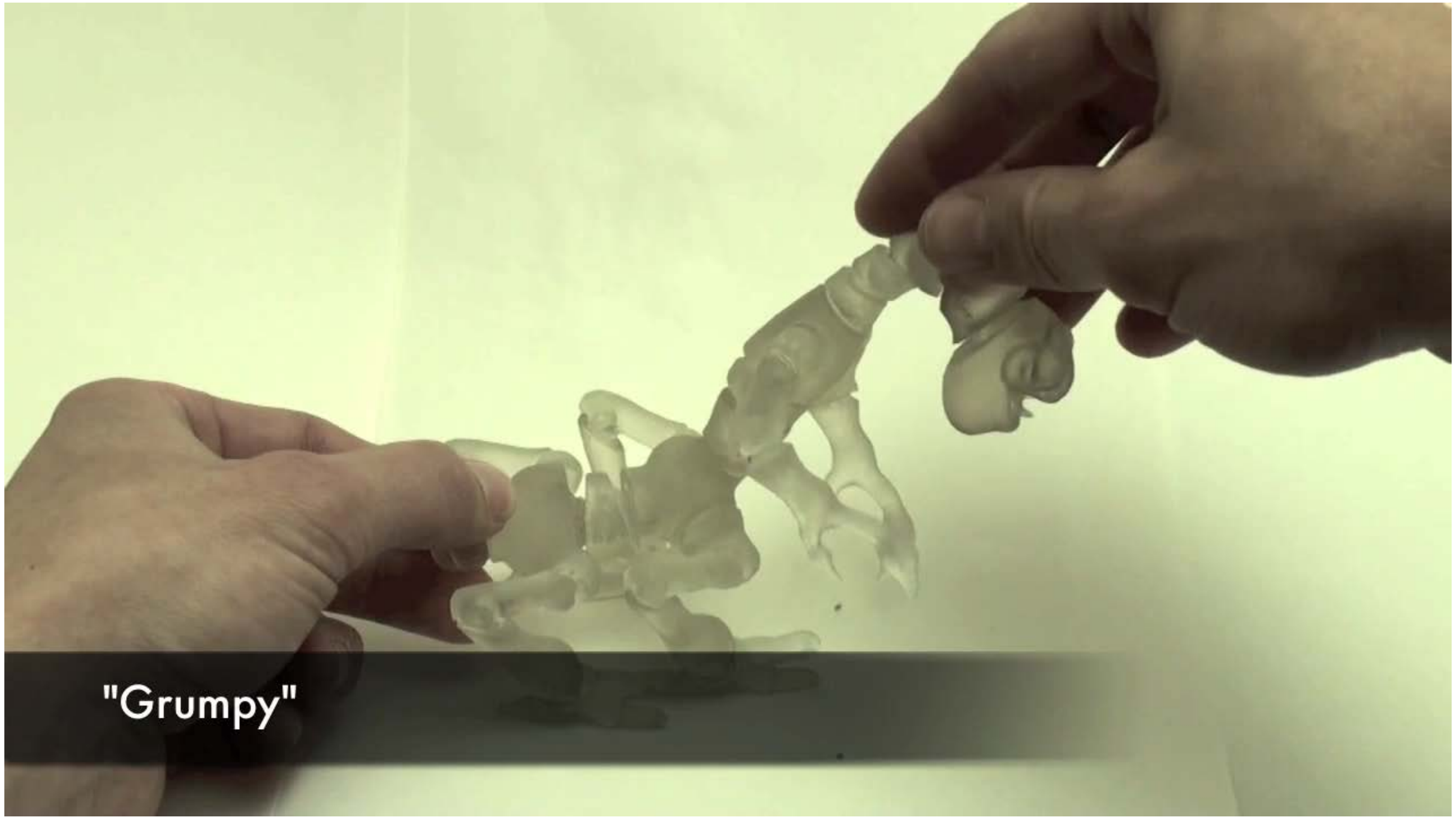

Fabricating articulated characters from skinned meshes [2012]

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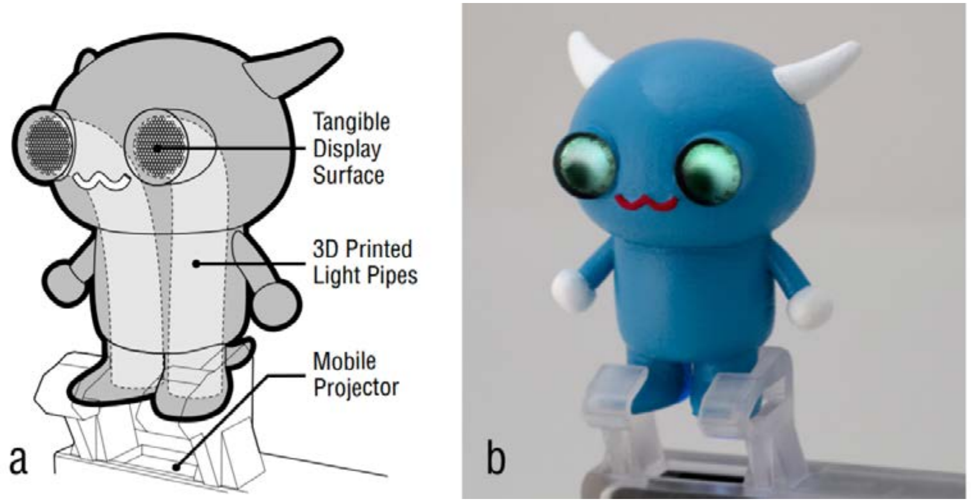
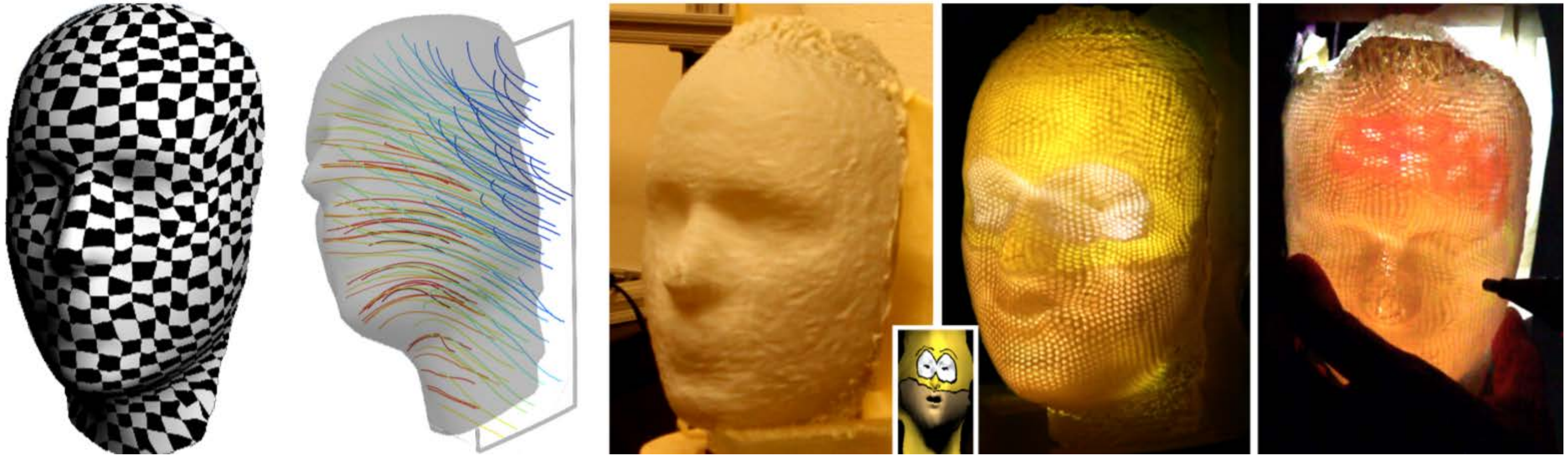
  - **Appearance**
  - **Integrity and deformation**
  - **High-Level Design**
  - **Process optimization**
  - **Frame works**

Fabrication in Graphics

- Appearance



Printed Optics: 3D Printing of Embedded Optical Elements for Interactive Devices [2012]



Computational light routing: 3D printed fiber optics for sensing and display [2014]

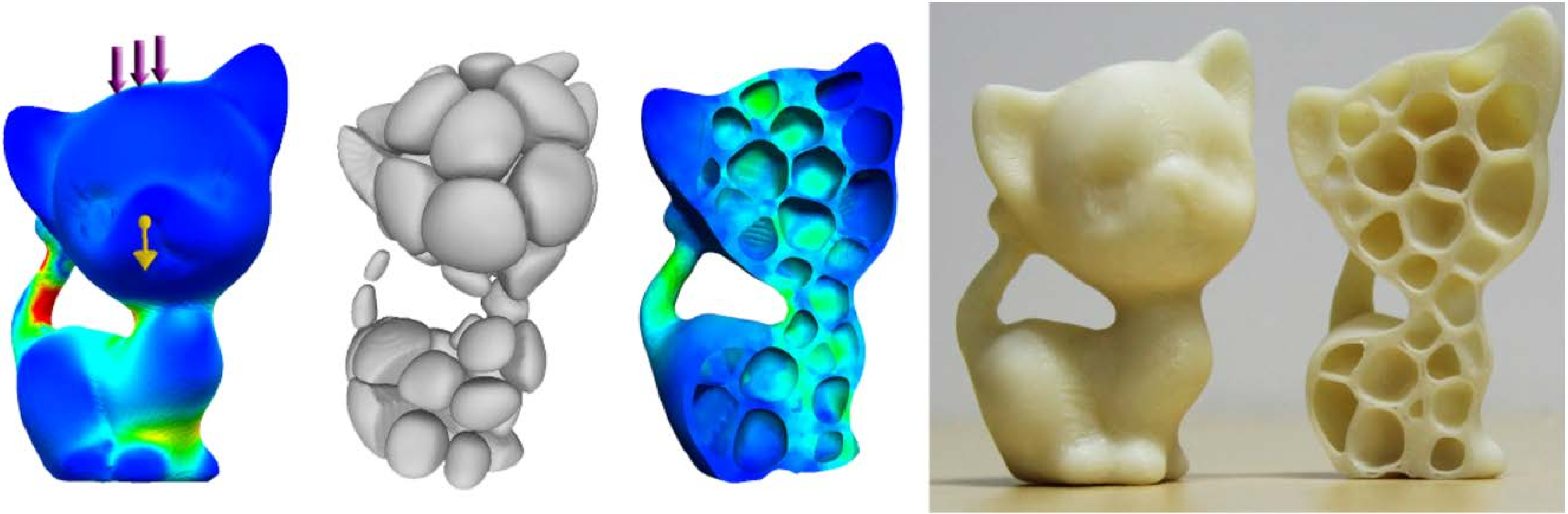
Fabrication in Graphics

- Appearance

Synthesis of filigrees for digital fabrication [2016]

Fabrication in Graphics

- Integrity



Build-to-last: Strength to weight 3d printed objects [2014]

Fabrication in Graphics

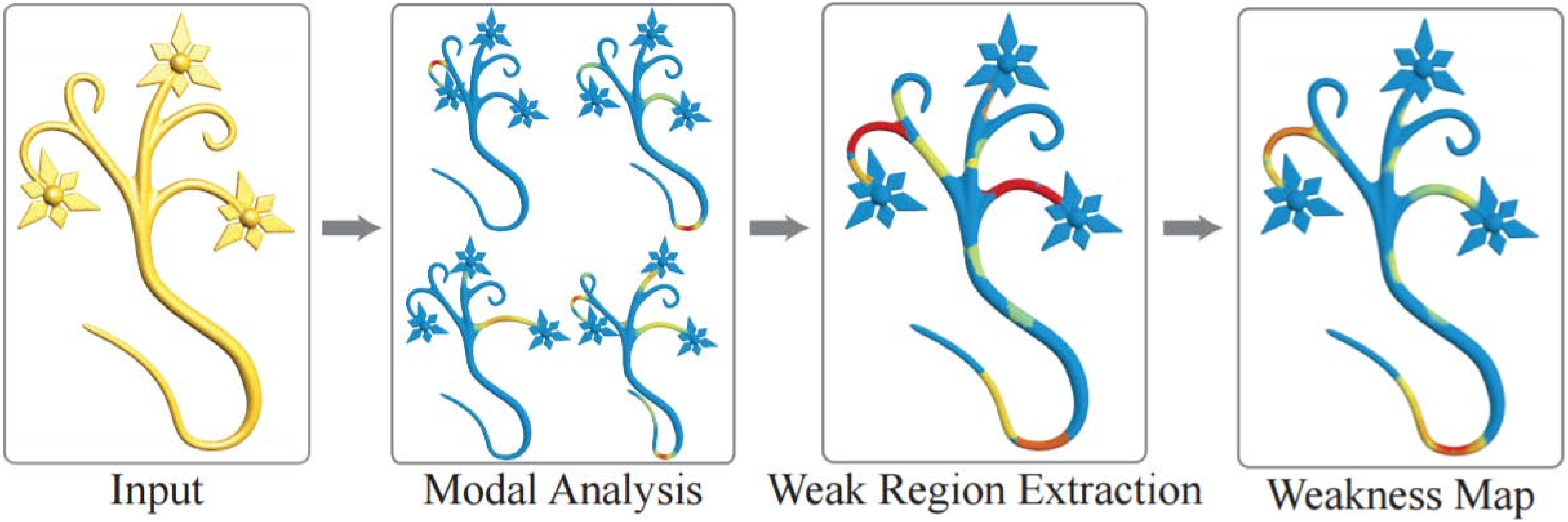
- Integrity

A System for High-Resolution Topology Optimization

Jun Wu, Christian Dick, Rüdiger Westermann

Fabrication in Graphics

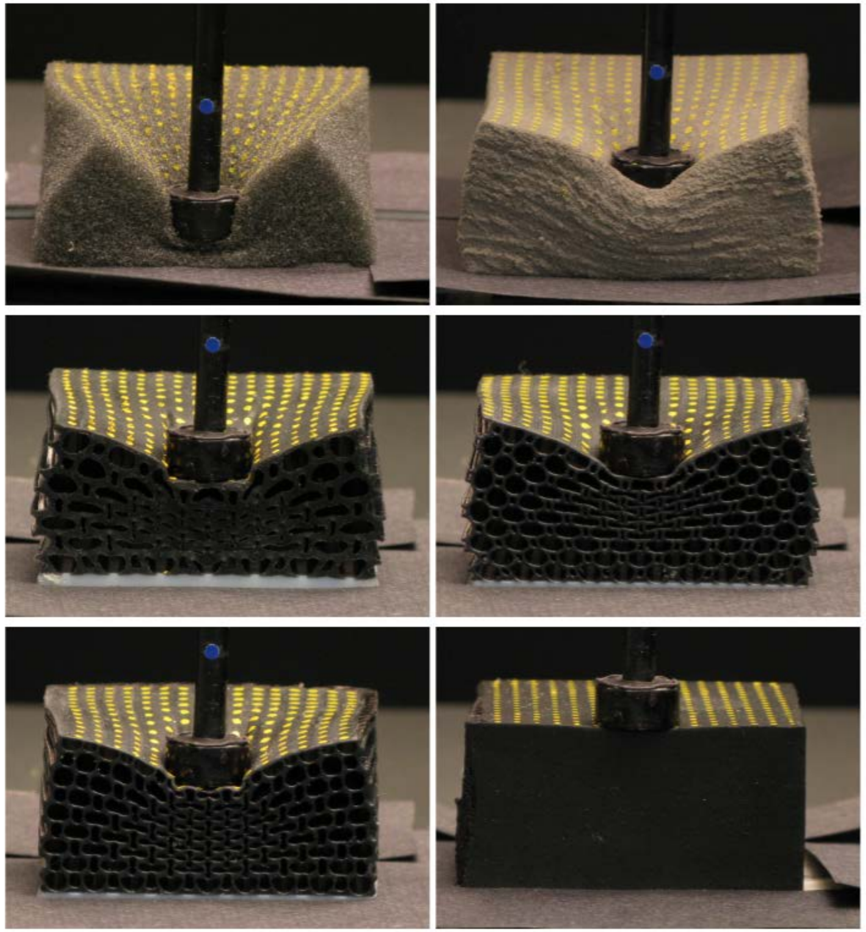
- Integrity

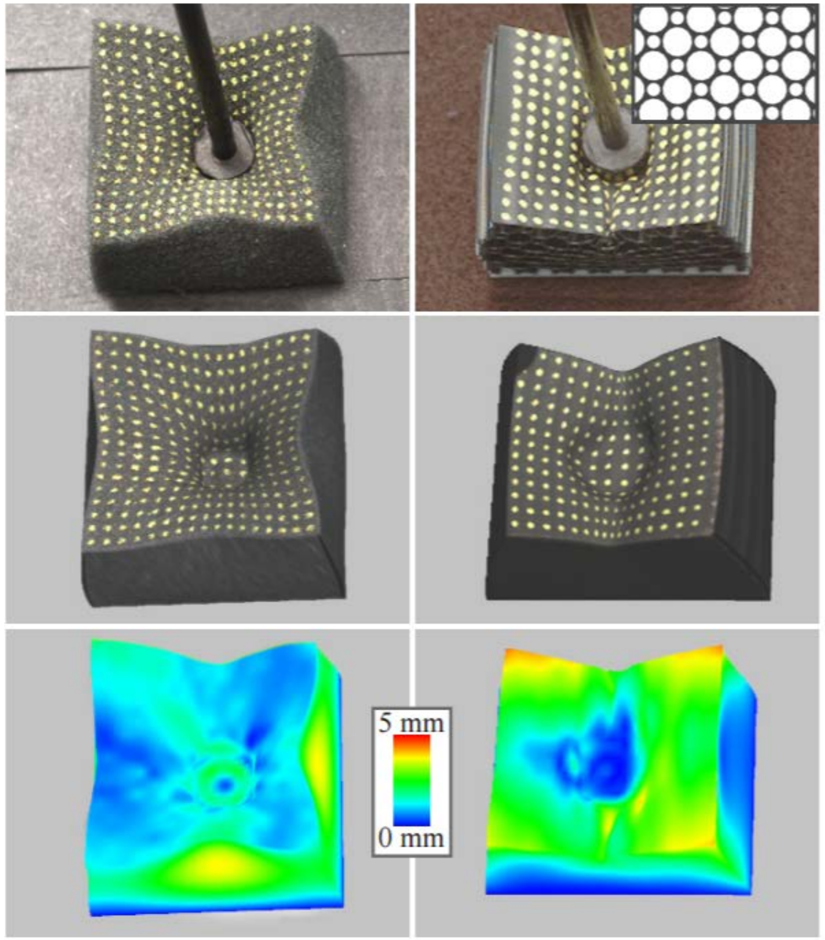


Worst-case structural analysis [2013]

Fabrication in Graphics

- Deformation Behavior

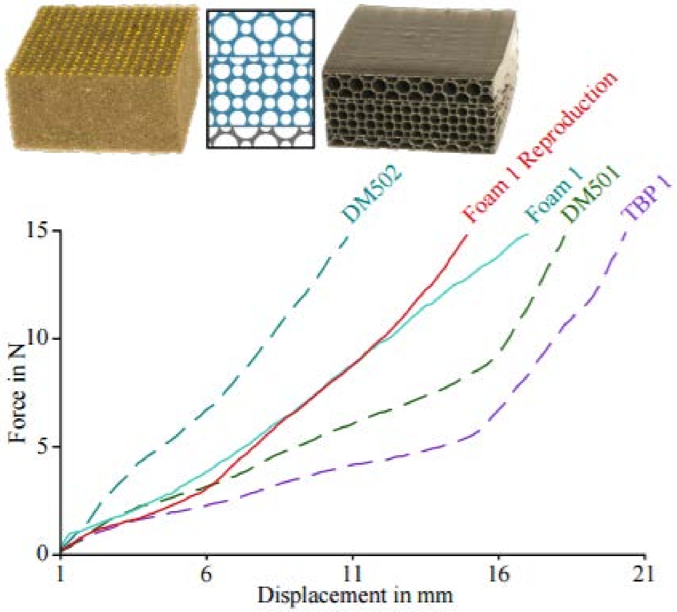


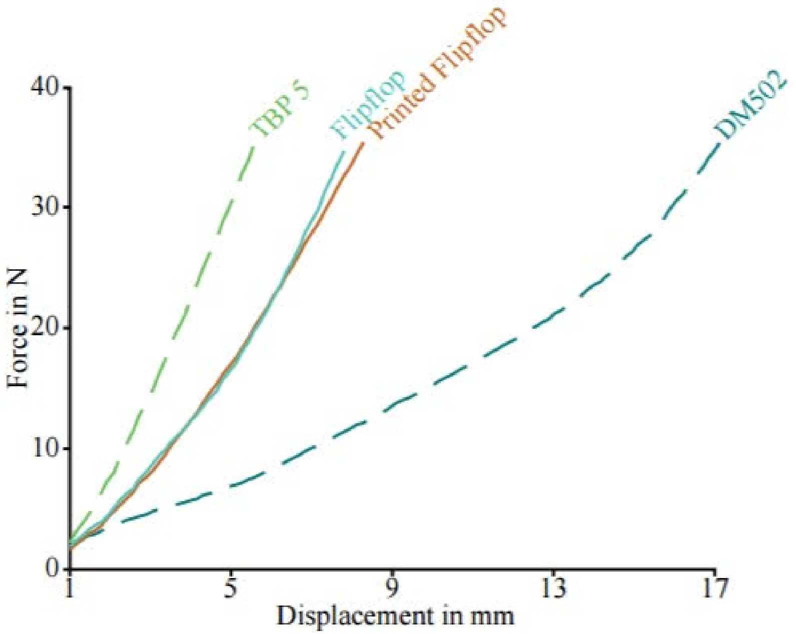


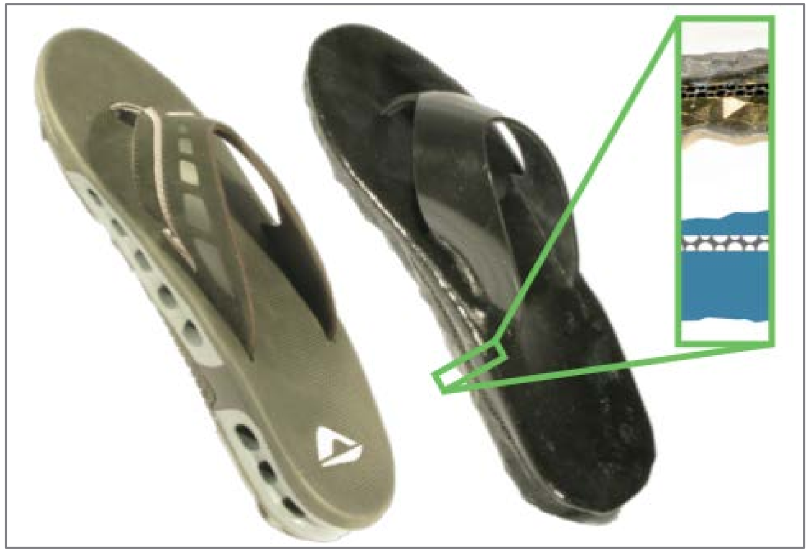
Design and fabrication of materials with desired deformation behavior [2010]

Fabrication in Graphics

- Deformation Behavior







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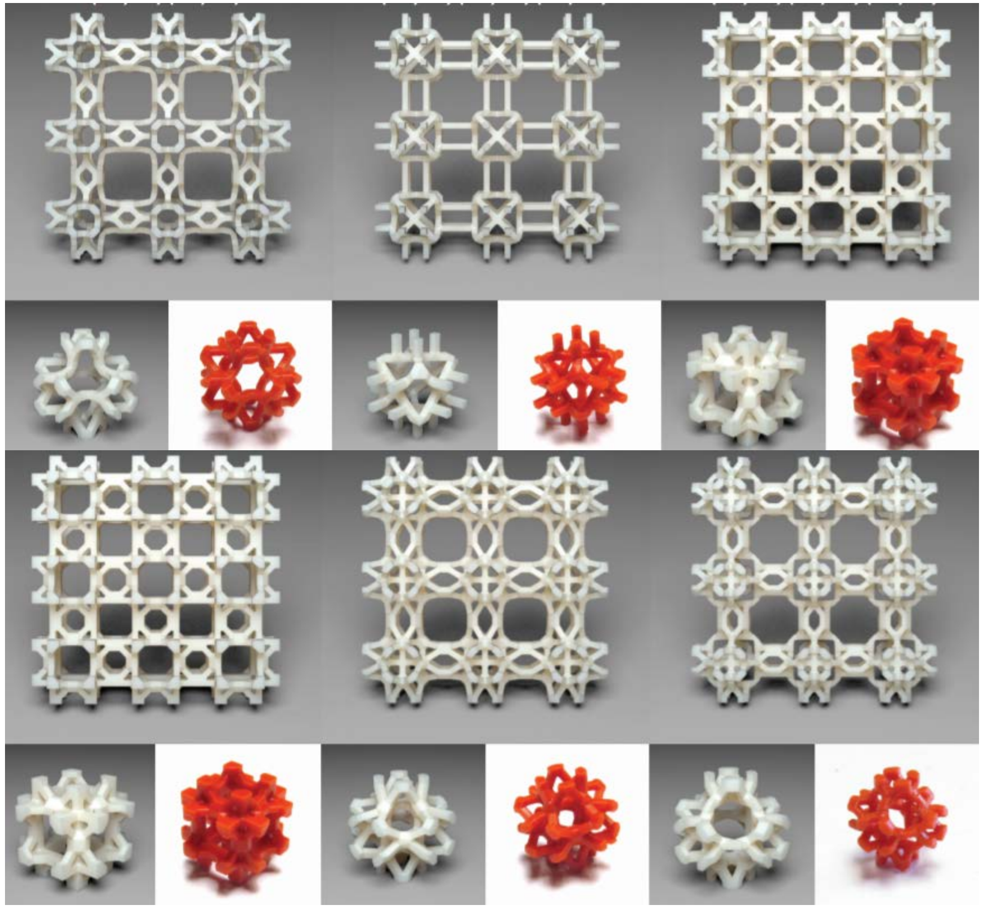
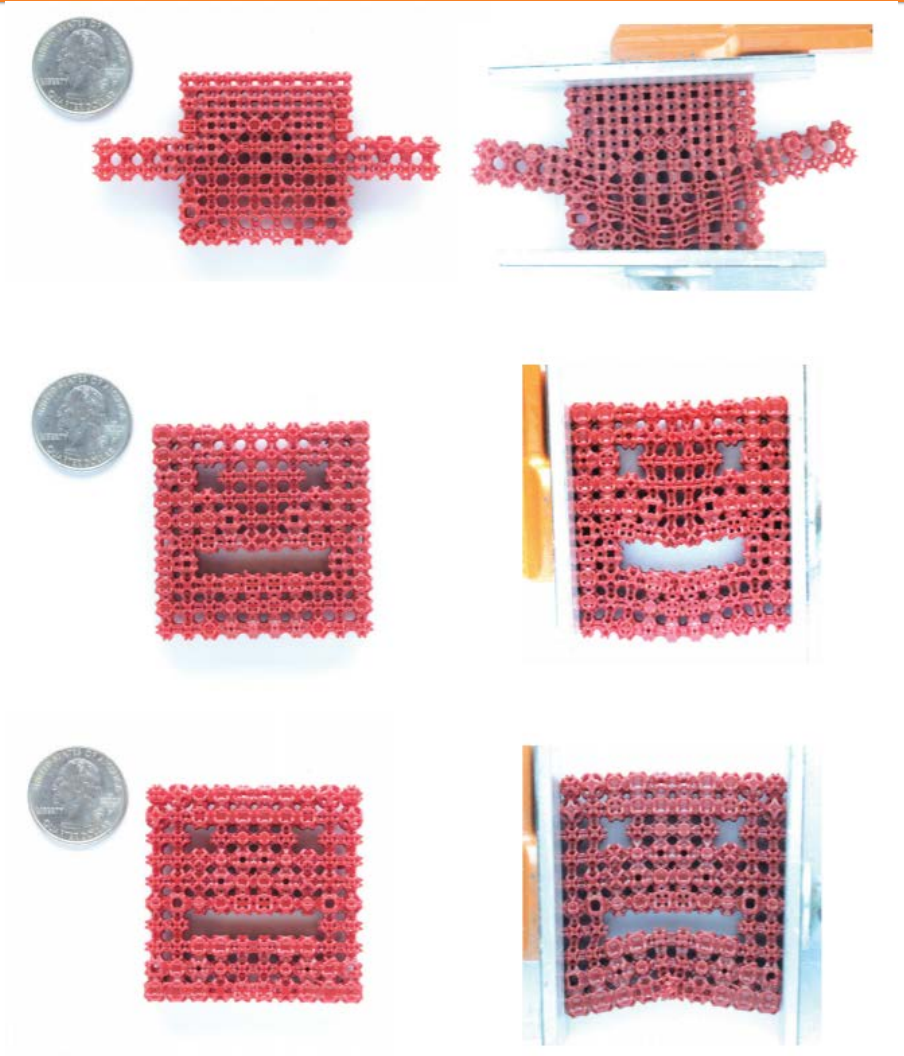
Fabrication in Graphics

- Cellular structures

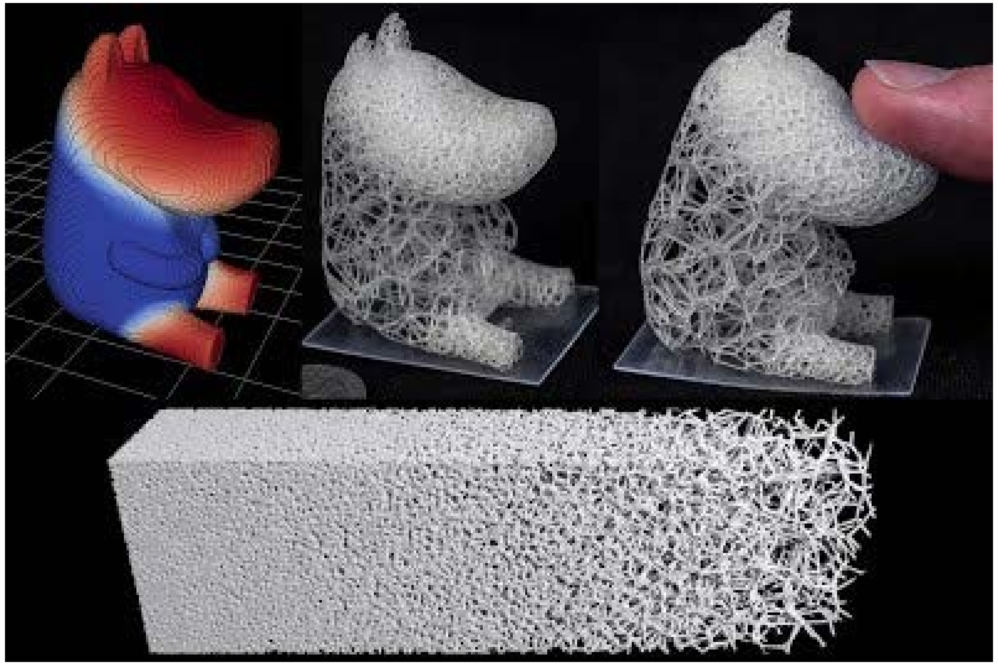




Elastic textures for additive fabrication [2015]

Fabrication in Graphics

- Cellular structures

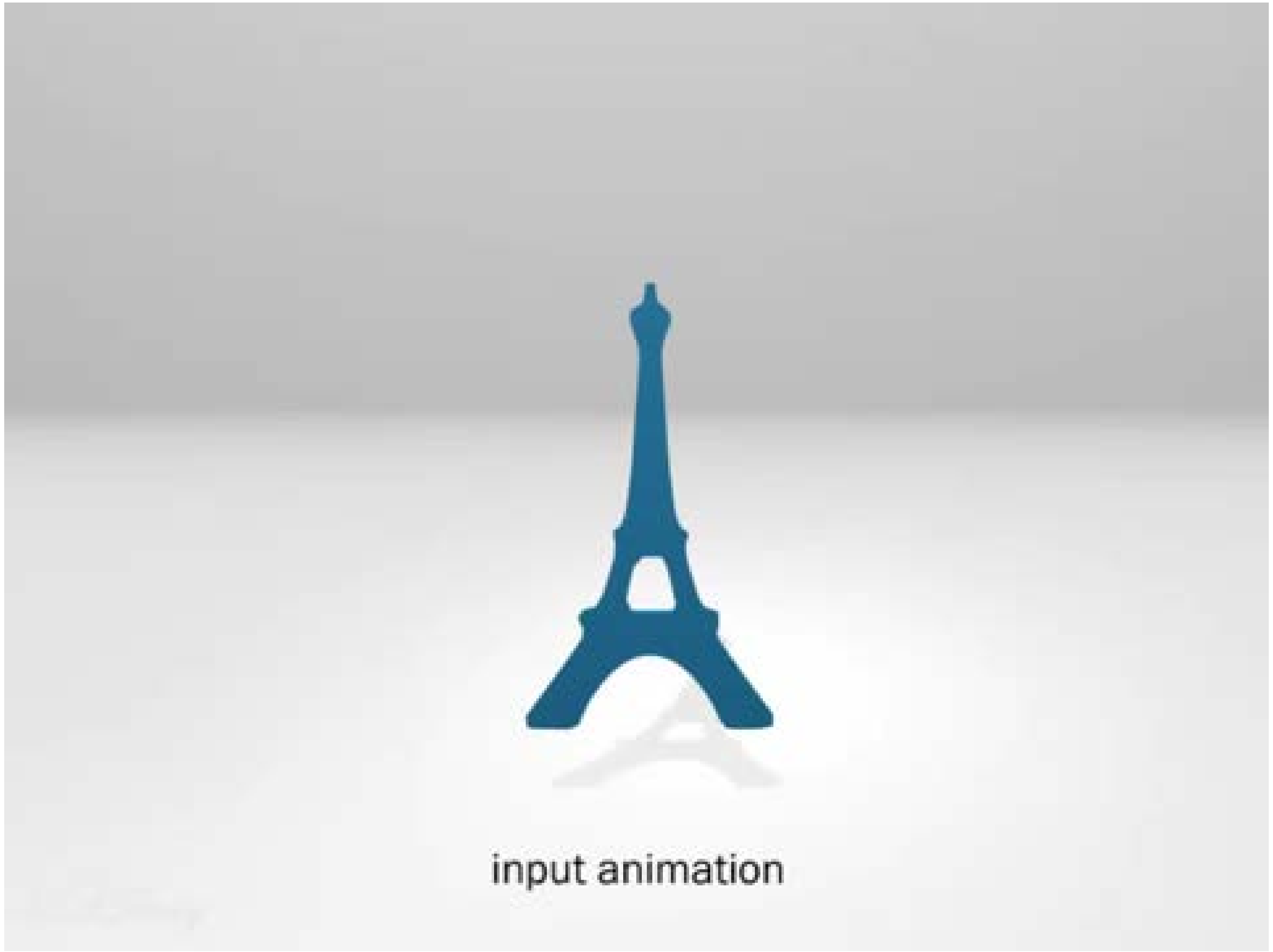


Procedural Voronoi foams for additive manufacturing [2016]

Microstructures to control elasticity in 3D printing [2015]

Fabrication in Graphics

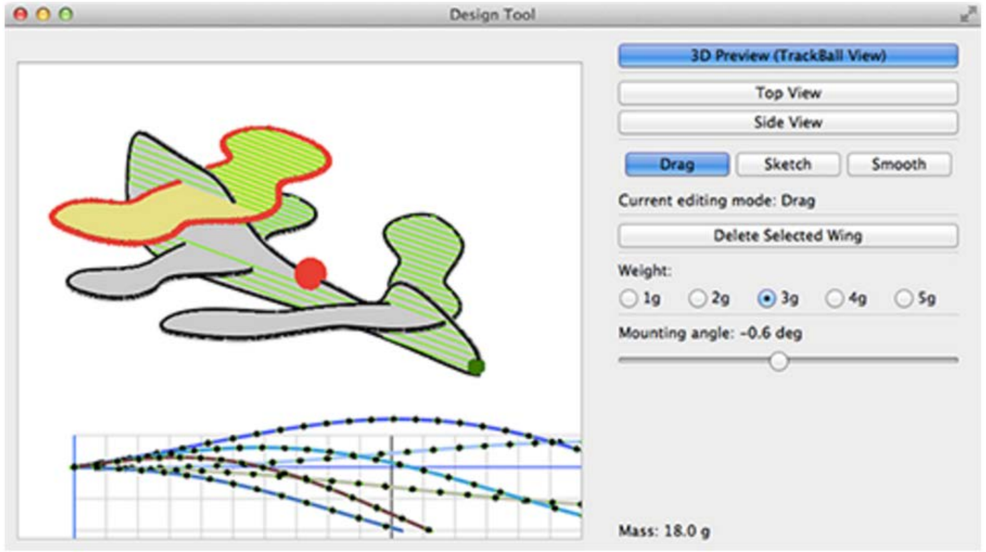
- Deformation Control



Computational design of actuated deformable characters [2013]

Fabrication in Graphics

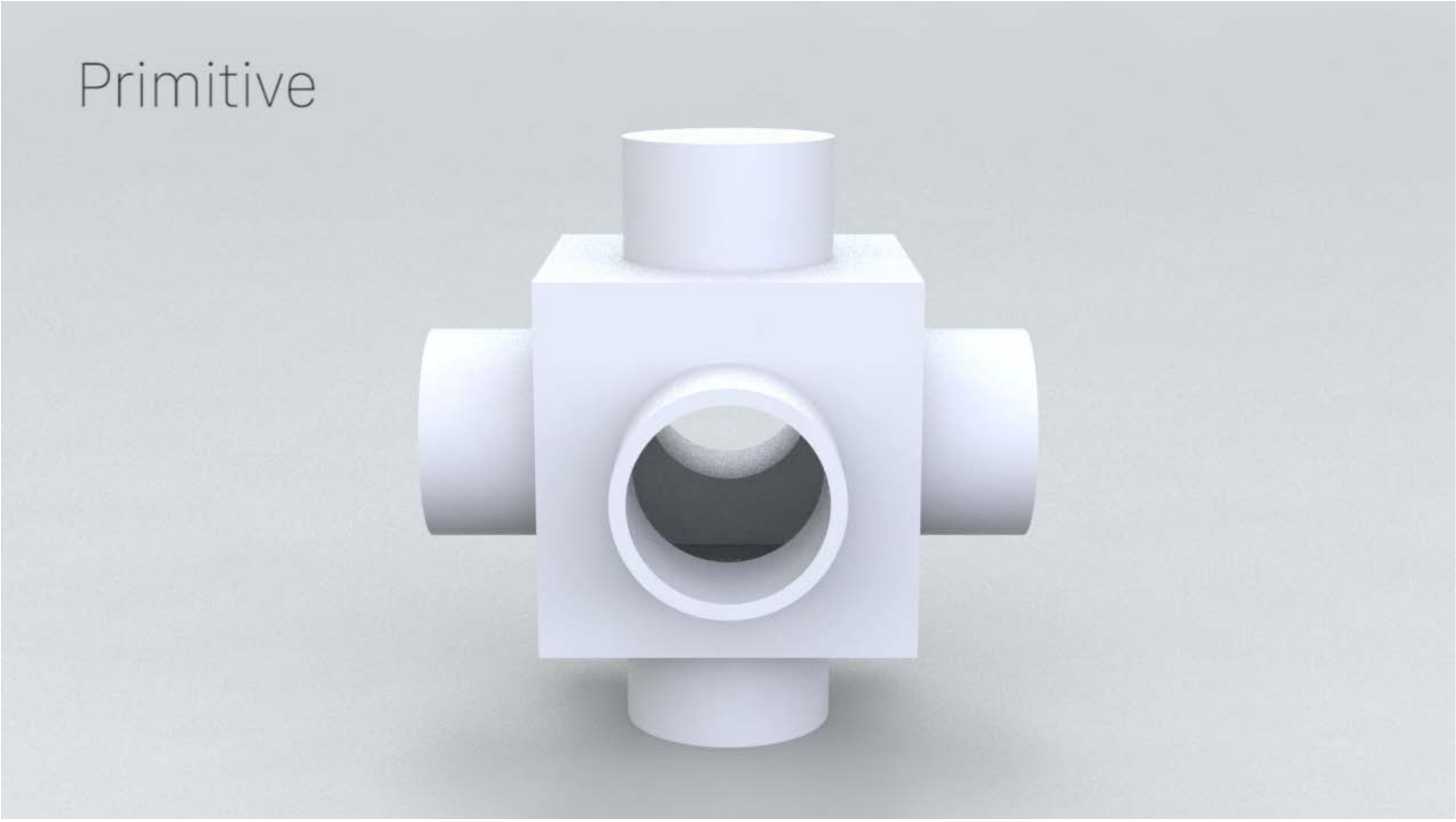
- High-level design



Pteromys: Interactive design and optimization of free-formed freeflight model airplanes [2014]

Fabrication in Graphics

- High-level design



Acoustic voxels: Computational optimization of modular acoustic filters [2016]

Fabrication in Graphics

- High-level design

Acoustic voxels: Computational optimization of modular acoustic filters [2016]

Fabrication in Graphics

- High-level design

Design and fabrication by example [2014]

Fabrication in Graphics

- High-level design

Autoconnect: Computational design of 3D-printable connectors [2015]

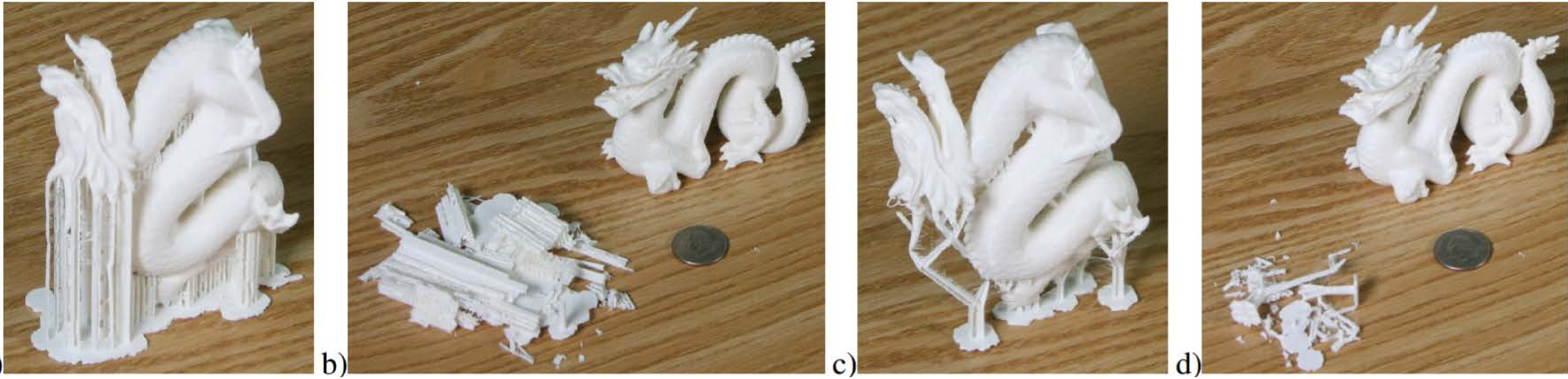
Fabrication in Graphics

- High-level design

Computational Design of Mechanical Characters [2013]

Fabrication in Graphics

- Process optimization



Clever support: Efficient support structure generation for digital fabrication [2014]

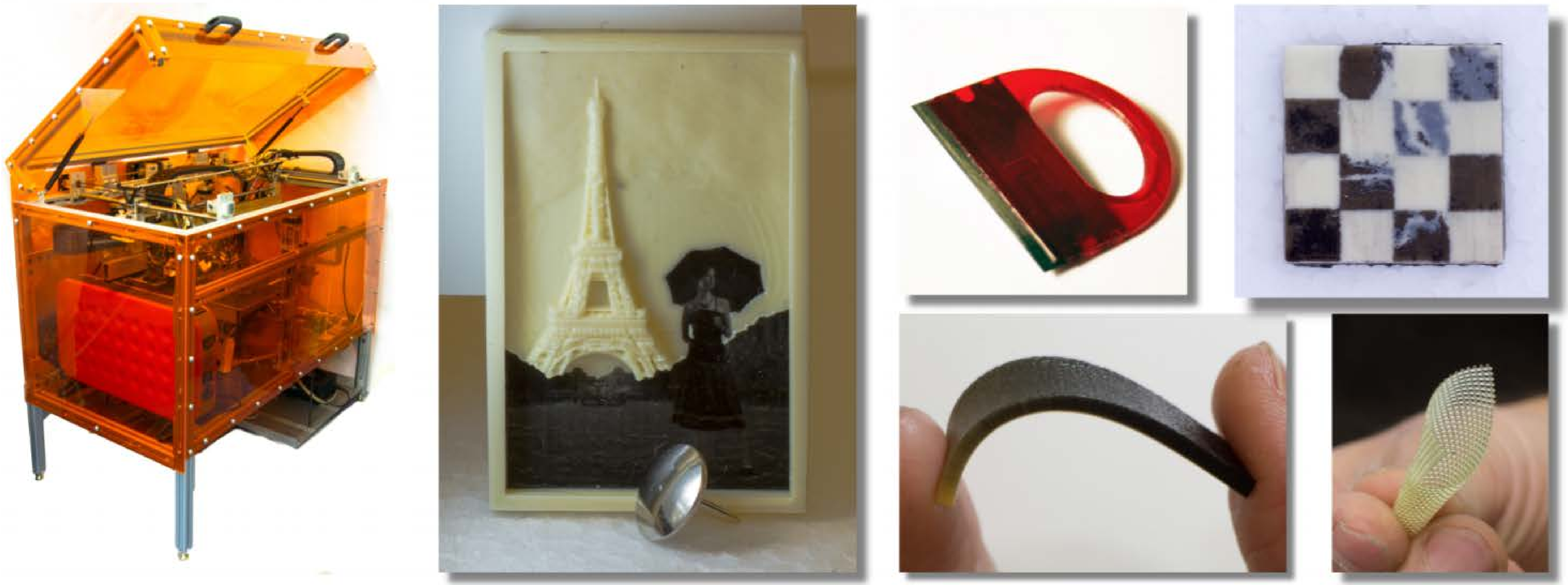
Fabrication in Graphics

- Process optimization

Chopper: Partitioning models into 3D-printable parts [2012]

Fabrication in Graphics

- Process optimization

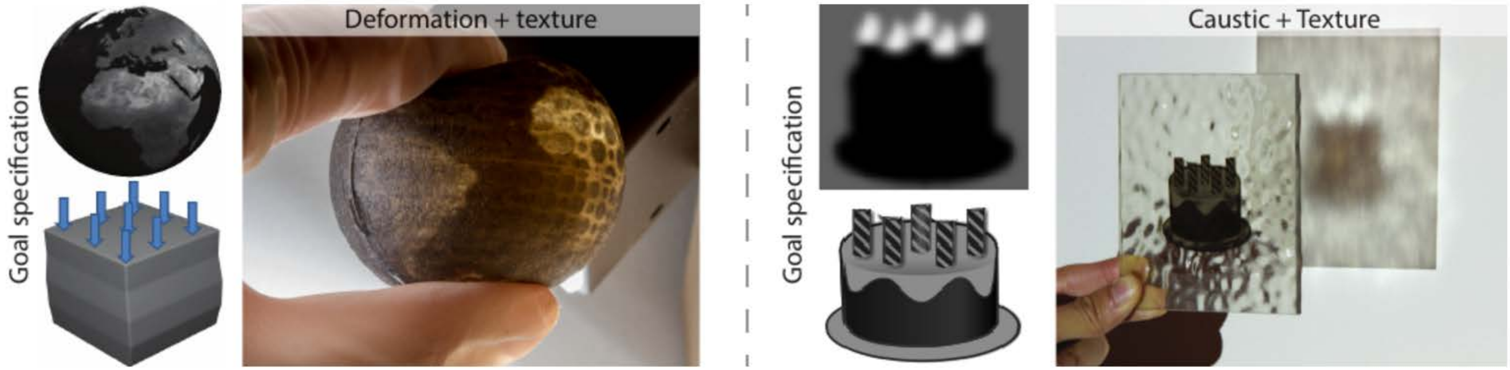


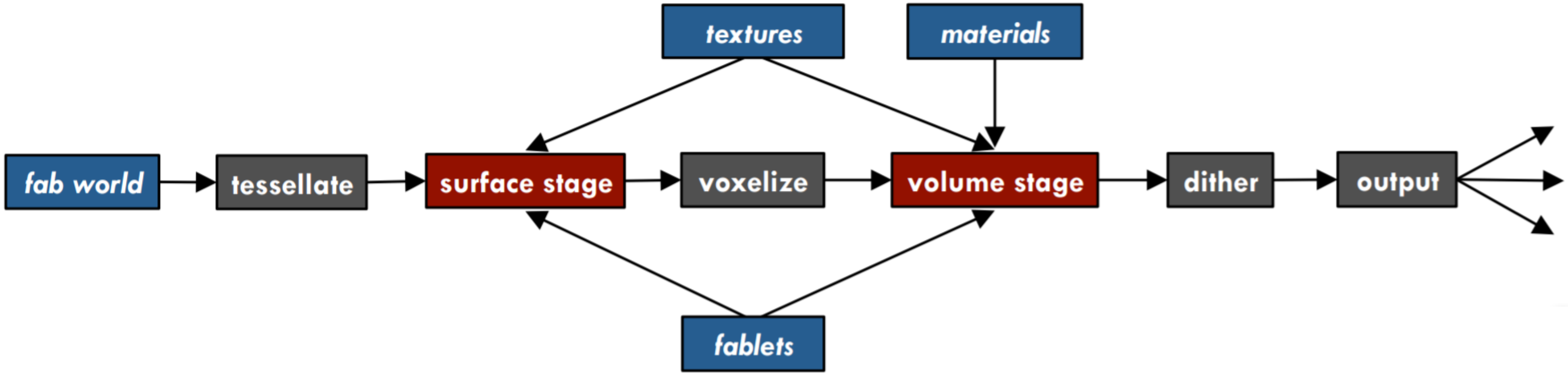
Multifab: A machine vision assisted platform for multi-material 3d printing [2015]

Fabrication in Graphics

- Frameworks

Spec2Fab: A reducer-tuner model for translating specifications to 3D prints [2013]





Openfab: A programmable pipeline for multi-material fabrication [2013]

Fabrication in Graphics

- LOTS more

What Does the Future Hold?

- Hierarchical Representations
- Leveraging large collections
- More objectives
- Procedural or purely objective based design
- Medical arena