Computational Tools for 3D Printing

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Part 4: Modeling and Analysis

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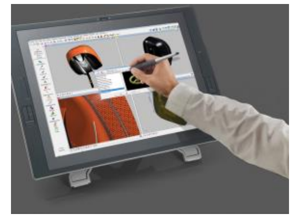
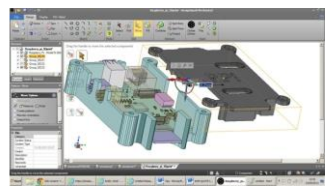
Modeling 3D Objects

- A difficult problem on its own:
  - 3D world on 2D displays
  - 3D manipulation using 2D (or 2.5D) devices
  - Complex: mostly done by experts
  - Issues relating to the digital representation





Challenges Specifically for Fabrication & Printing (not just Graphics)

- Need to actually be constructed or printed:
  - Fitting parts
  - Finding intersections
  - Defining connectors
  - Checking printability
- Need to be physically plausible:
  - Appearance
  - Materials
  - Weight
  - Forces

Geometry

Physics

Two Approaches

1. Inverse Modeling

Specification → Optimization → Model

2. Interactive modeling:

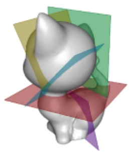
Interaction → Model

Examples of Inverse Design

- Appearance fabrication
- Deformable objects fabrication
- Basic idea:

Input		**Output**
A given shape + High level specification	→	A recipe for fabricating the object (shape, material, structure…)

More Inverse Modeling Examples

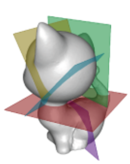


Chopper: Partitioning Models into 3D-Printable Parts
Linjie Luo, Ilya Baran, Szymon Rusinkiewicz, Wojciech Matusik
ACM Transactions on Graphics, 31(6), (SIGGRAPH Asia), 2012

Make It Stand: Balancing Shapes for 3D Fabrication
Romain Prévost, Emily Whiting, Sylvain Lefebvre, Olga Sorkine-Hornung, *ACM Trans. Graph.* 32, 4, Article 81 (July 2013)

Build-to-last: strength to weight 3D printed objects.
Lin Lu, Andrei Sharf, Haisen Zhao, Yuan Wei, Qingnan Fan, Xuelin Chen, Yann Savoye, Changhe Tu, Daniel Cohen-Or, and Baoquan Chen. 2014 *ACM Trans. Graph.* 33, 4, Article 97 (July 2014)

More Inverse Modeling Examples

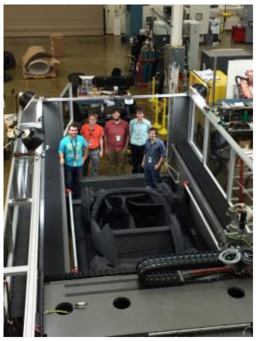


Specify: shape and size

Specify: balance

Specify: strength to a given weight

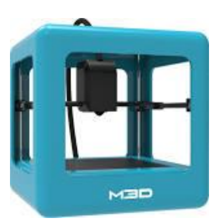
Strati: First 3D Printed Car

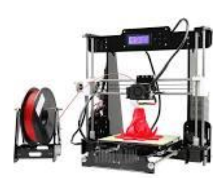


- Made by **Local Motors** for the International Manufacturing Technology Show (**IMTS**)
- Strati = “layers” in Italian
- 18 months of design
- 44 hours of printing

Usually Print Volume is Limited

- Typically 10cm x 10cm x 10cm up to 50cm x 40cm x 30cm
- Printing large objects requires chopping and assembly



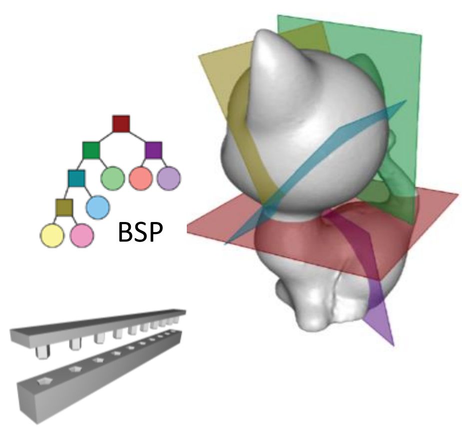


Chopper: Two Challenges

- How to segment?
- How to connect?

Chopper: Two Challenges

- How to segment?
  - Use planes to define parts
  - Cut top down recursively
- How to connect?
  - Use male/female connectors:



Overview

Pick a bunch of potential cuts

↓

Evaluate them and find the best ones

↓

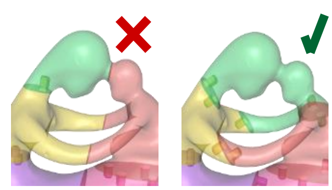
Recurse on pieces that are still to big

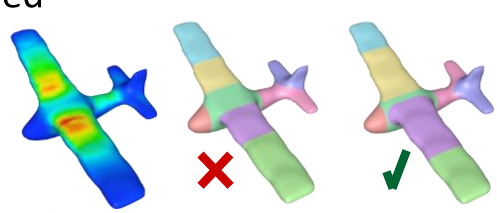
↓

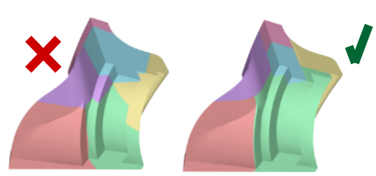
Place connectors on cross-sections

Optimization Objective

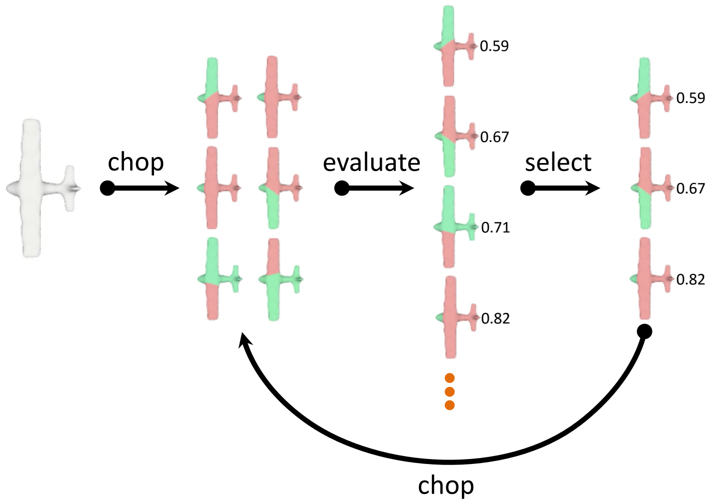
- Connector feasibility
- Part fragility
- Structural soundness when assembled
- Number of parts
- Printing volume utilization
- Seam aesthetics







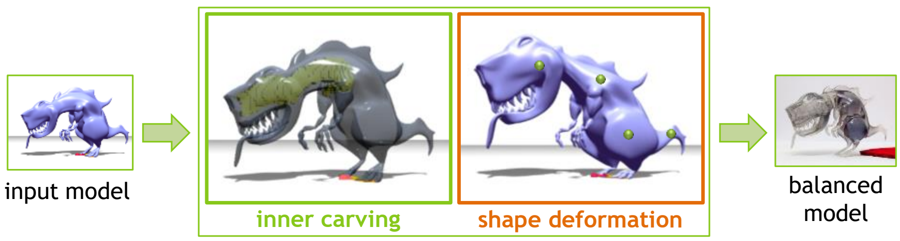
Optimization: Beam Search [Lowerre 1976]



Make It Stand Challenge

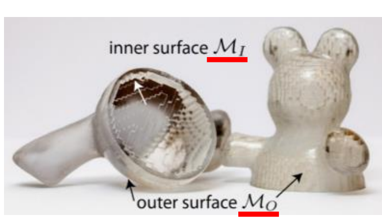
- Designing things that can really stand:

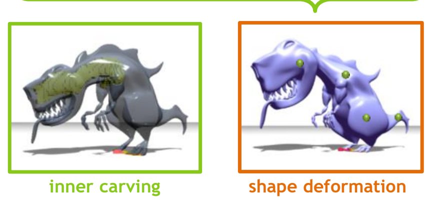
Overview



Optimization

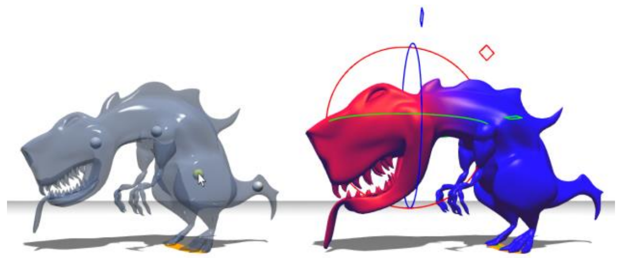
$$\underset{\mathcal{M}_I,\mathcal{M}_O}{\operatorname{argmin}}\ (1-\mu)\, \underbrace{E_{CoM}(\mathcal{M}_I,\mathcal{M}_O)}_{\text{does it stand?}} + \mu\, \underbrace{E_{\mathcal{M}}(\mathcal{M}_O)}_{\text{similarity to original shape}}$$





User Assistance

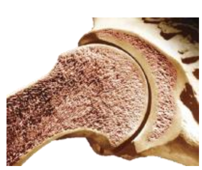
- Changing the shape using handles



Build-to-Last Challenge

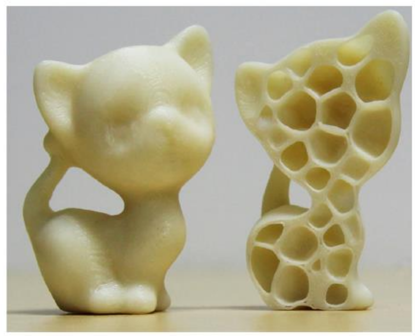
- Reduce the object weight while providing a durable 3D printout sustaining given forces.
- Inspiration from porous structure
  - Lightweight
  - Strong
  - Ability to absorb energy, vibration

BMW engine mounting bracket

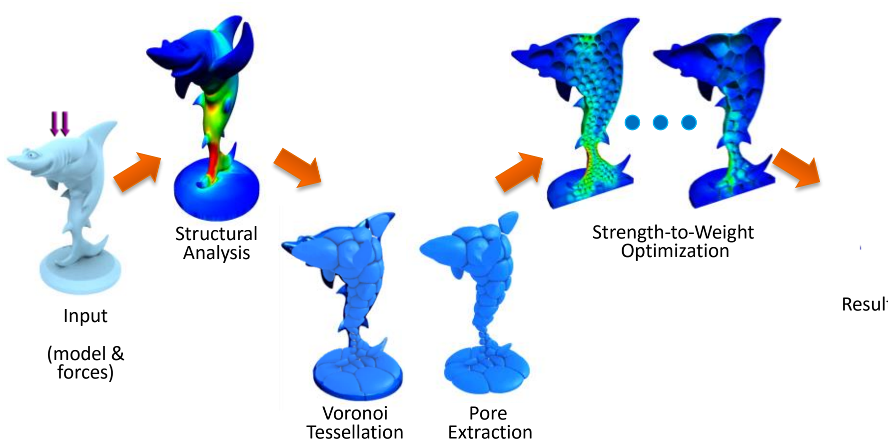


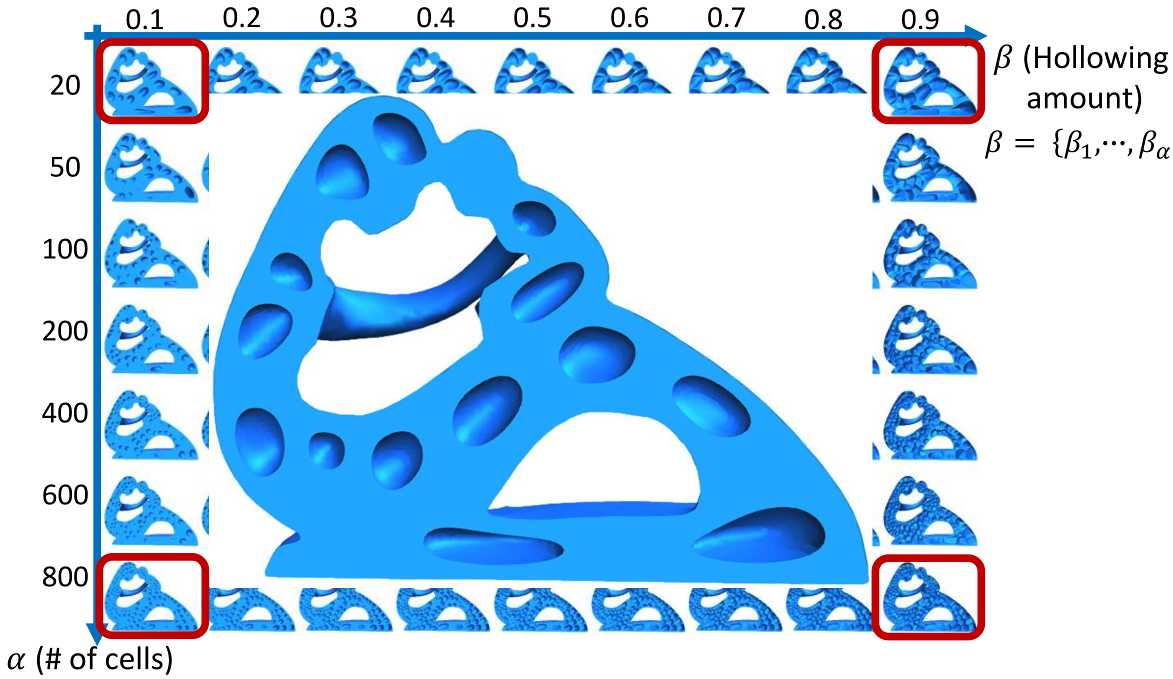
Basic Idea

Introducing the ***honeycomb-cell structure***, which is of minimal material cost while providing strength in tension.



Overview





Optimization

- Objective: $\underset{\alpha,\beta}{\operatorname{argmin}}\, W_s(\alpha, \beta) \quad s.t. \quad SM(S,\ F) < \chi$

Shape

Forces

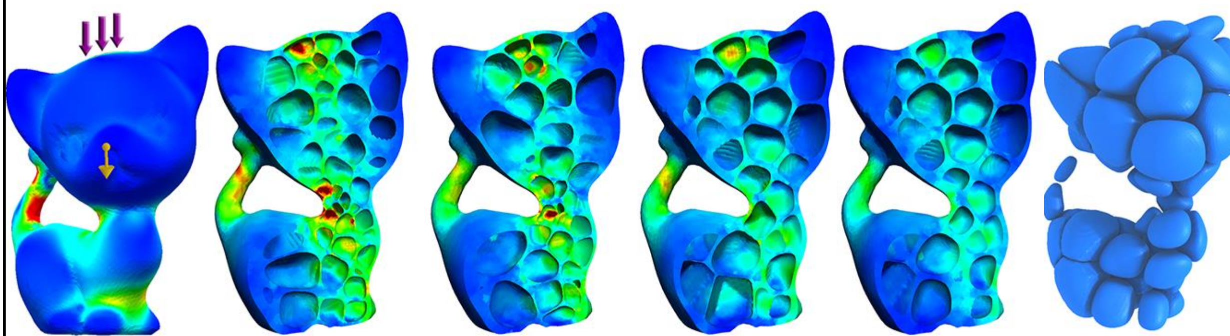
Yield point = stress at which a material begins to deform plastically

Weight (volume)

Strength (stress map)

- Two loops for optimizing α and β
  - Outer loop: optimize α for compactness
  - Inner loop: optimize β for sustaining stress

Results



Initial setting & Stress map

Iterations

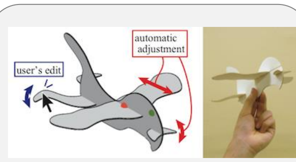
Optimal result

3D pores

$125.07\ cm^3$

$50.79\ cm^3 (40.6\%)$

More Examples of Inverse Design Objectives



[Umetani *et al.*, 2014]

Flight ability

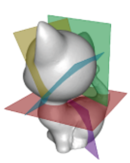
[Baecher *et al.*, 2014]

Spin ability

Inverse Design Methodology

- Given a 3D shape (usually boundary surface), optimize some objective (size, balance, strength) by changing shape parameters:
  - Inner shape – does not change outside appearance
  - Outer part – usually want to constrain not to differ too much from original shape

Modeling vs. Modifying a Given Input Shape



- Shape and size: finds segmentation

- Balance: modify internal and external shape

- Strength to weight: modify internal shape mostly

Creating a Whole New Model?

Yuki Koyama, Shinjiro Sueda, Emma Steinhardt, Takeo Igarashi, Ariel Shamir, Wojciech Matusik

AutoConnect: Computational Design of 3D-Printable Connectors

ACM Transactions on Graphics, Volume 34, Number 6, (SIGGRAPH Asia Conference Proceedings), Article No. 231, 2015

BibTeX More »

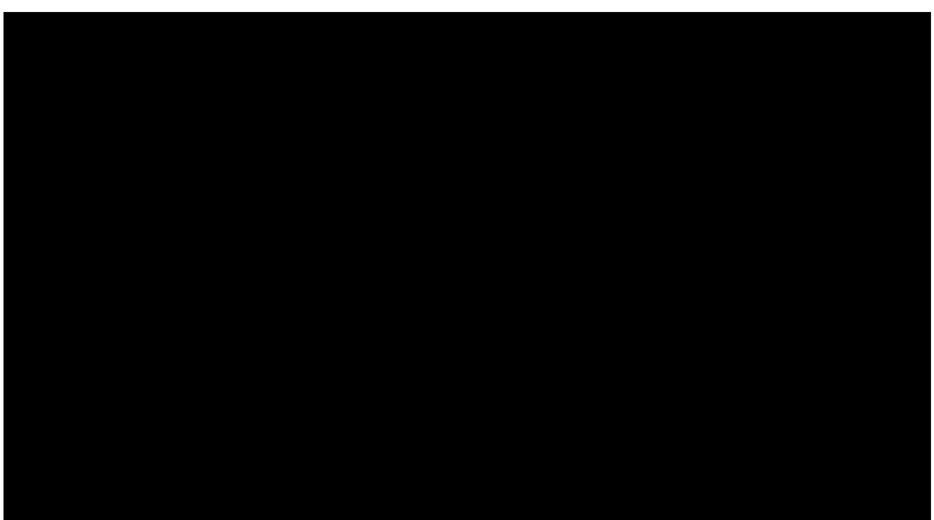
Makers Make Connectors

Objective

- Input — Two geometries
  - Position / orientation
  - Weights
  - Auxiliary parameters (e.g., free directions)
- Output — A customized connector
  - Automatically generated
  - Fabricable (physics, geometry)
- No initial shape to begin with

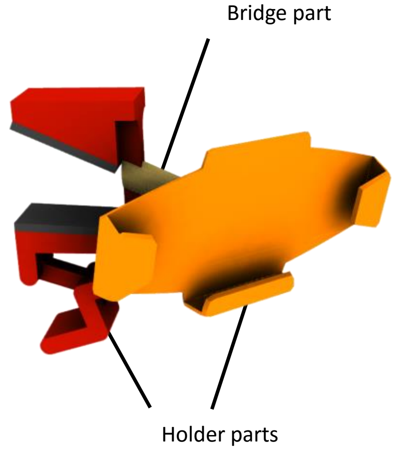
Example

Example 2

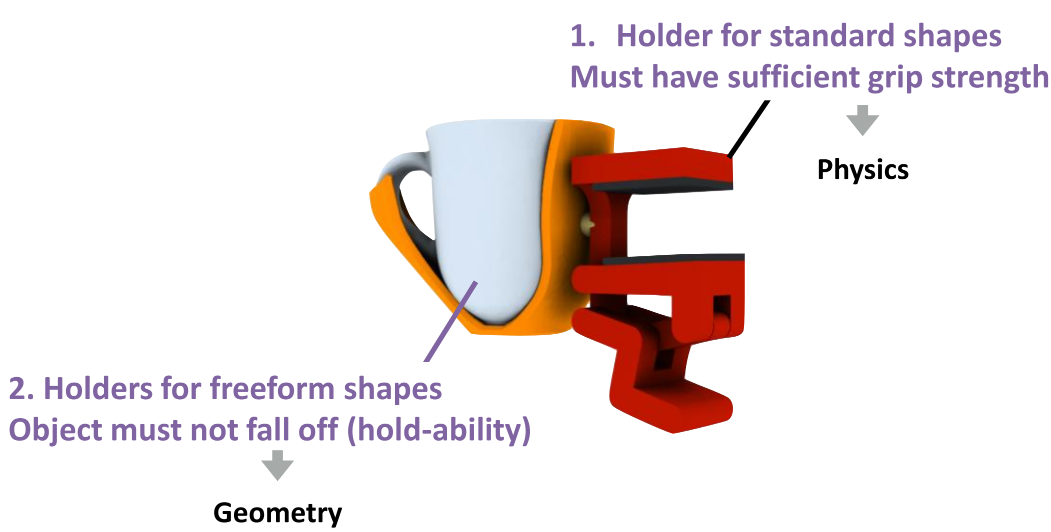


Connectors Definition

- Two holder parts
  - Each holder connects/holds one of the target objects
- Bridge part
  - Simple bar connecting the two holders



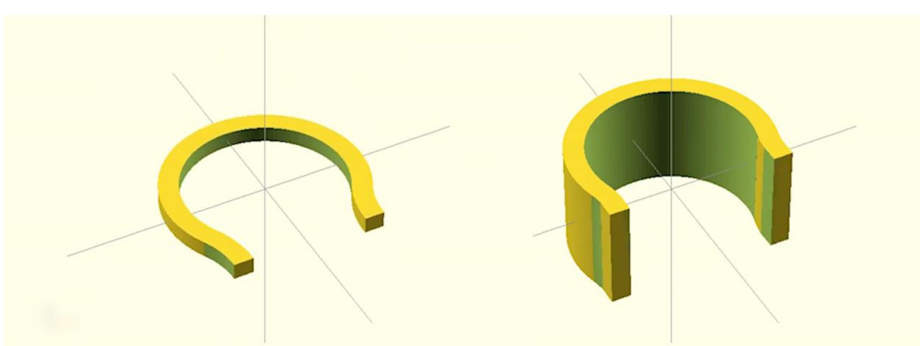
Two Holder Types



Holders Database

Parametrized Holders

Every holder is parametrized by a few parameters

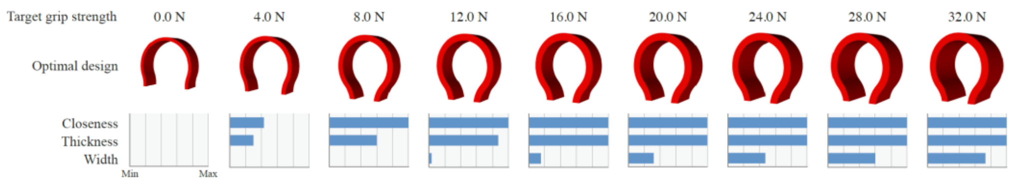


e.g. height e.g. closeness

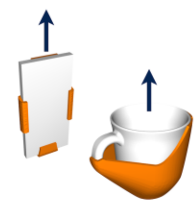
Considering Grip Strength

Freeform Holders by Area Expansion

Two Types of Optimizations

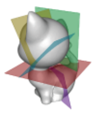


- Optimizing holder parameters for Grip Strength



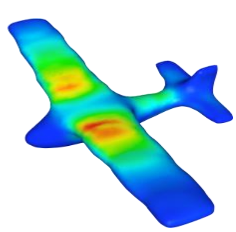
- Optimizing surface for Holdability

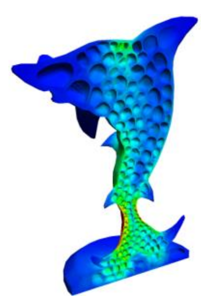
Physical Considerations

-  : avoid cutting at weak points in the mesh
-  : balancing
-  : avoid large pores at weak points
-  : avoid slipping or falling

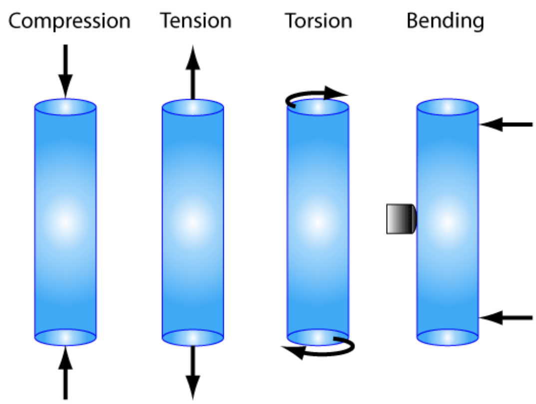
Structural Analysis

- In many cases there is a need to analyze the “strength” or “weakness” of the shape





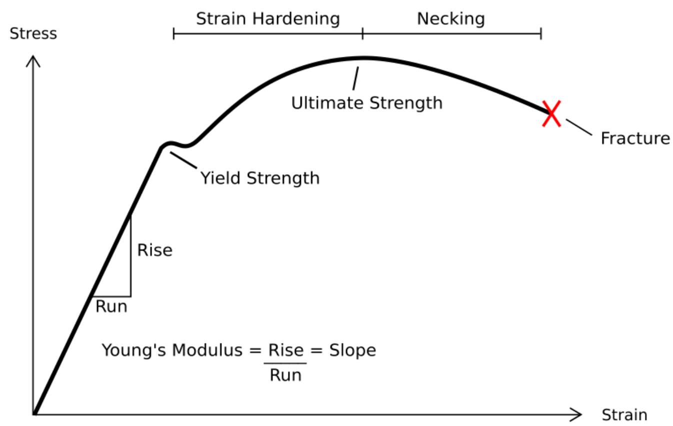
Forces & Load



Yield

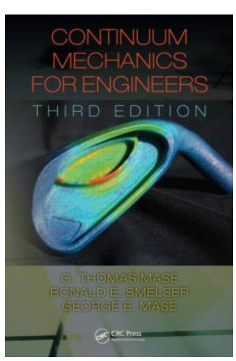
- A **yield strength** or yield point is the **material property** defined as the stress at which a material begins to deform plastically.
- Prior to the yield point the material will deform elastically and will return to its original shape when the applied stress is removed. Once the yield point is passed, some fraction of the deformation will be permanent and non-reversible.

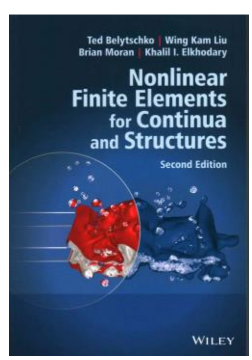
Strain vs. Stress



Continuum Mechanics: Structural Analysis

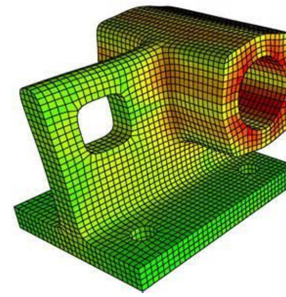
- Standard method in engineering uses Finite Elements Methods

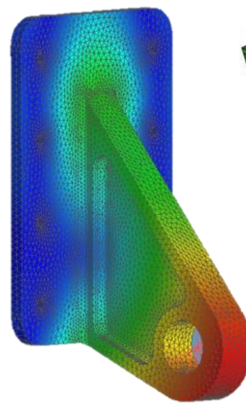




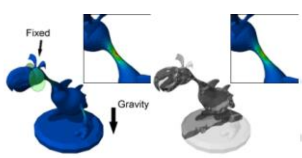
FEM

- Define a variational formulation
- Discretize the space
- Define basis functions
- Solve (iterative)
- Post processing

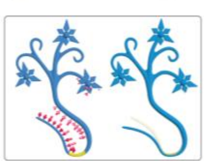




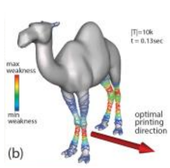
In Graphics



Stress Relief: Improving Structural Strength of 3D Printable Objects
[Stava et al. SIG 2012]



Worst-case Structural Analysis
[Zhou et al. SIG 2013]



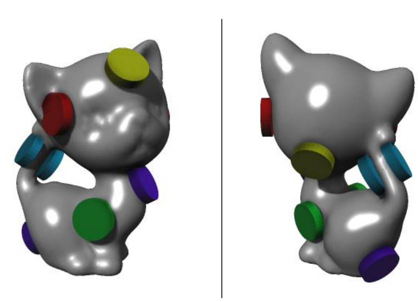
Cross-sectional Structural Analysis for 3D Printing Optimization
[Umetani & Schmidt SIGA 2013]

Three Key Questions for Fabrication

1. What is the applied load?
2. What are failure locations?
3. How to fix failures?

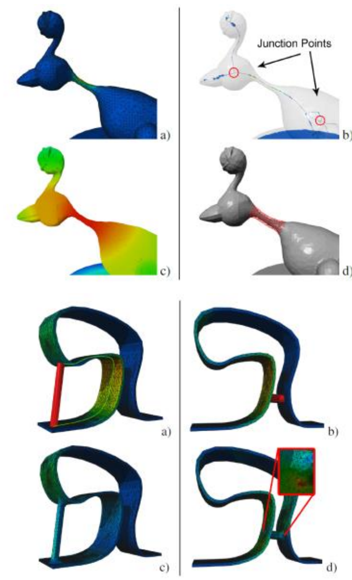
Stress Relief – Pinching Load

- Compute “Pinch Grip” locations:
  - Label triangle on convex hull as potential grip site for first finger
  - Cast ray in predefined direction to determine second triangle
- Filter grips based on biomechanical criteria
- Compute load using model from biomechanics



Stress Relief

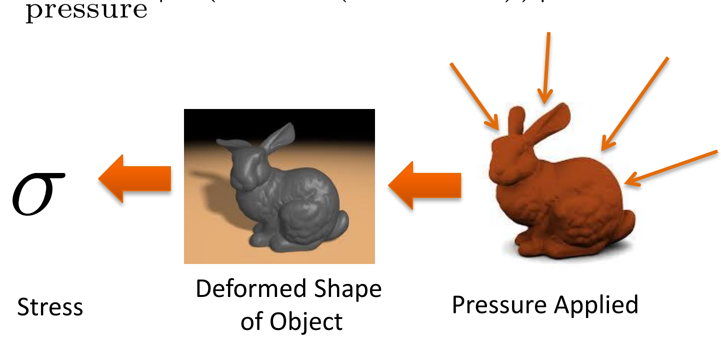
- Finite Element Analysis for all orientations and grip locations
- Fixing failures
  - Automatically thicken thin parts of the object
  - Add struts to support parts of the object
  - Hollow parts of the object to reduce weight



Worst-Case Structural Analysis

- Find a load that maximizes stress in the object

$$\max_{\text{pressure}} \left|\sigma\left(\text{shape}\left(\text{pressure}\right)\right)\right|$$



Worst-Case Structural Analysis

- Compute failure locations by finding stresses that exceed a threshold
- No fixing discussed

How does a structure break ?

Structure breaks at **slender parts**

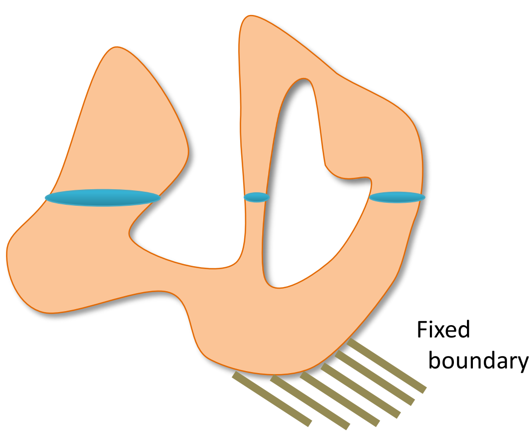
Structure breaks by **bending**

How a beam bends?

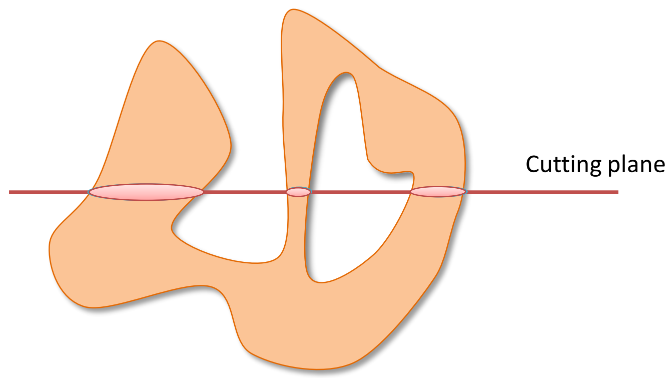
Cross-sectional Structural Analysis

- Requires just the surface mesh to perform analysis of the stress
- Treats objects as if they are beams

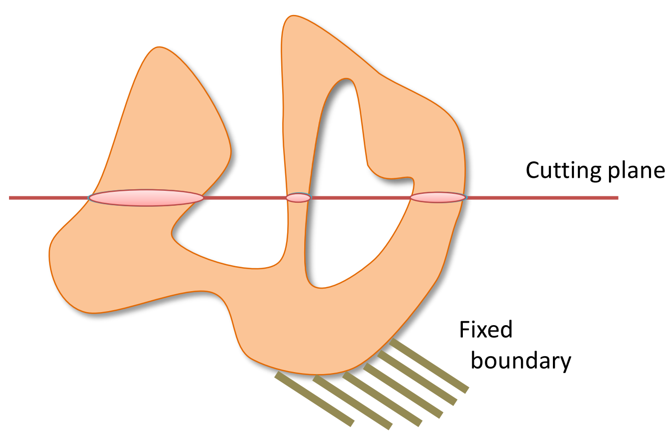
Compute Cross Sections



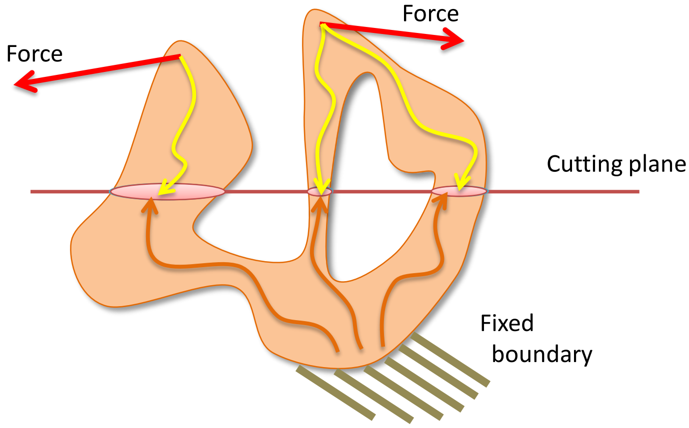
Divide object into two pieces using a cutting plane



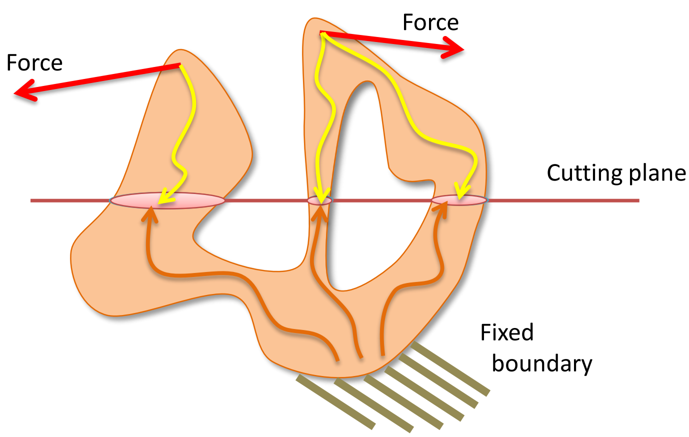
Fix boundary on one piece



Apply Forces



Compute maximum stress on cross sections



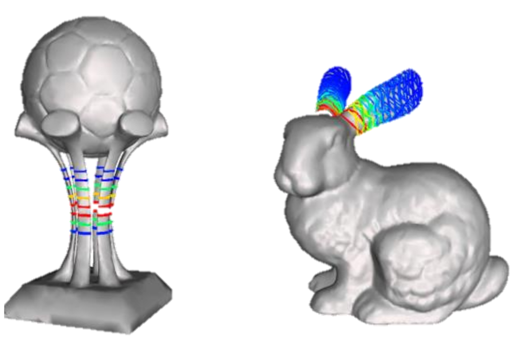
Weak Cross Sections Performance

- 13 directions of cross section, 32 slices in each direction

|T| = 17k
n-sample=60k
time = 0.18sec

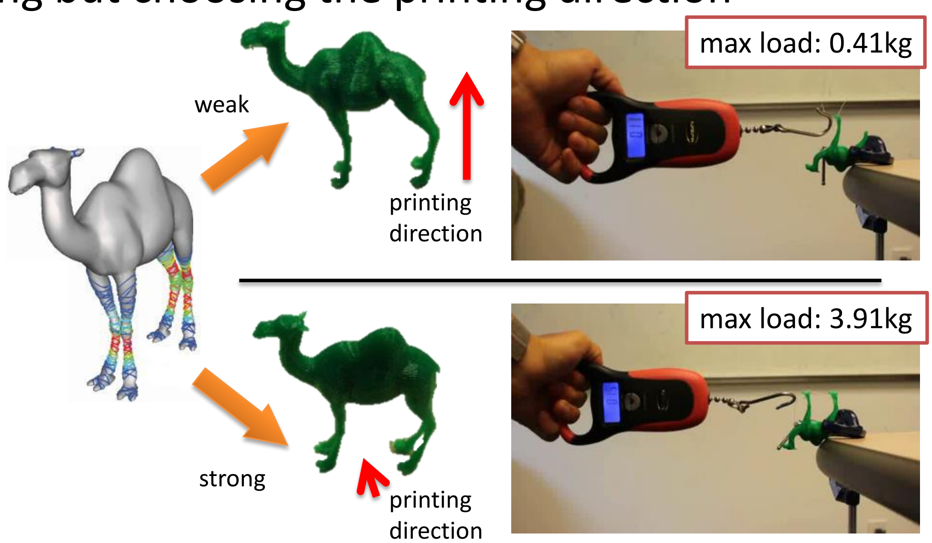
|T| = 34k
n-sample=200k
time = 0.31sec

|T| = 600k
n-sample=414k
time = 3.8sec



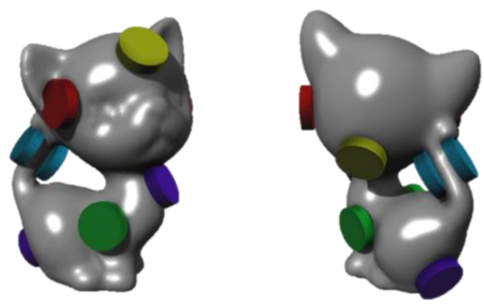
Application

- Not fixing but choosing the printing direction



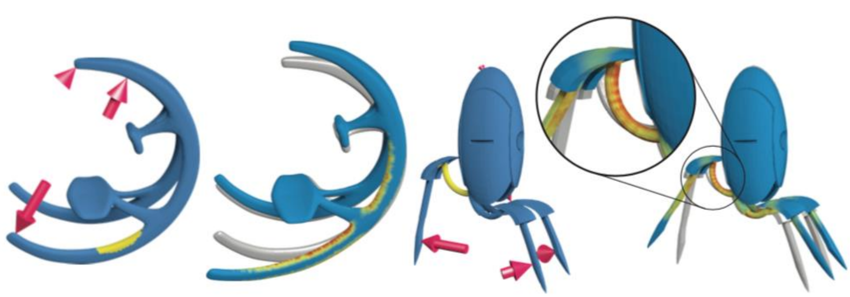
Structural Analysis Using Finite Elements

- Choose loading conditions
- FEM Solve for each loading condition



Worst-Case Analysis

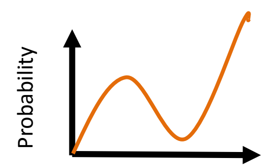
- Solving for multiple forces is too slow, so find most destructive force



- Finding this single force sample is slow and it may be unrealistic

New: Stochastic Finite Elements

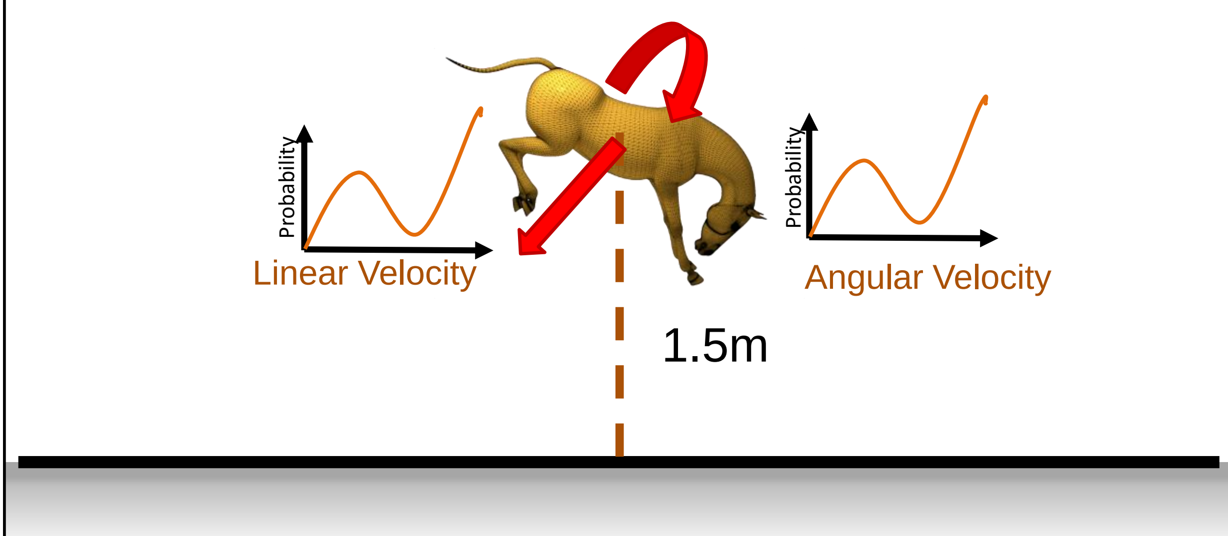
- Succinctly describe many forces as distributions
- Perform Finite Element Analysis on Force Distributions Instead



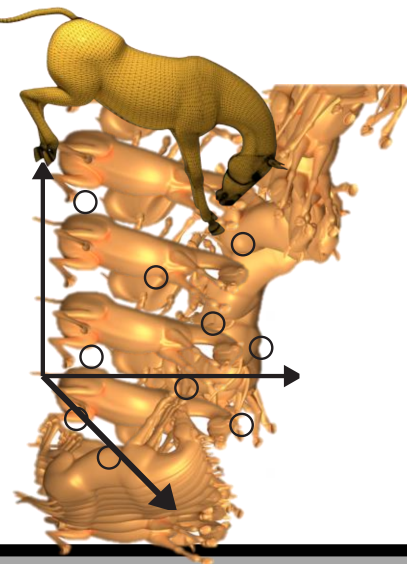
Stochastic Structural Analysis for Context-Aware Design and Fabrication

Timothy Langlois, David I.W. Levin, Daniel Dror, Ariel Shamir, Wojciech Matusik - *Conditionally Accepted SIG Asia 2016*

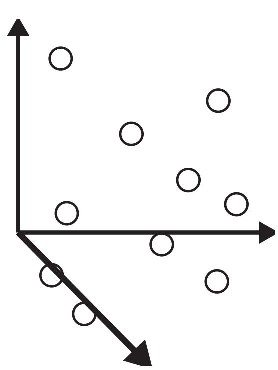
Generate Distributions via Sampling



Scene – Drop Test

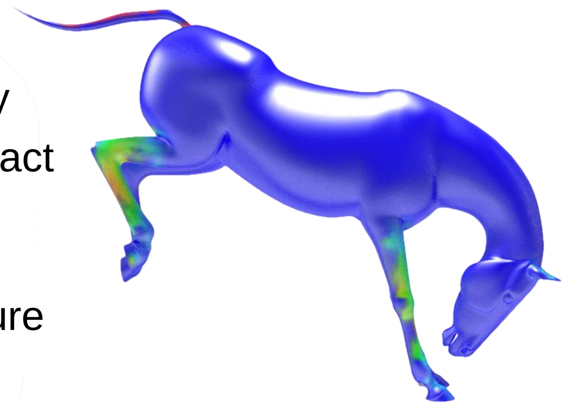


Operate in Reduced Sample Space



Fast Stochastic Analysis using Reduced Space

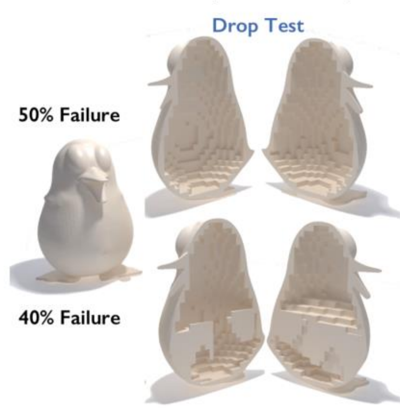
1. Unlike previous methods, encodes context efficiently
2. Handles complicated contact scenarios
3. Expresses reliability compactly as a single failure percentage



Probability of Failure: 71%

Stochastic Topology Optimization

- Because distributions are easy to compute via sampling, the method can be used for topology optimization



Back to Modeling

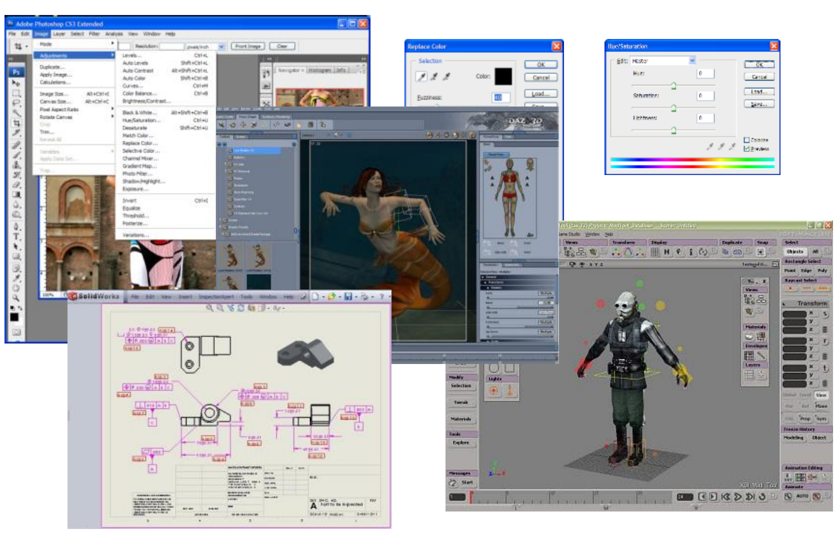
1. Inverse Modeling

Specification → Optimization → Model

2. Interactive modeling:

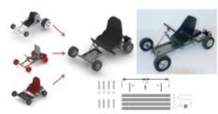
Interaction → Model

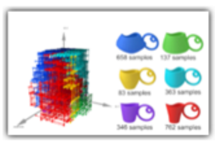
Modeling from Scratch is a Challenge

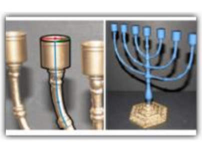


Interactive Modeling

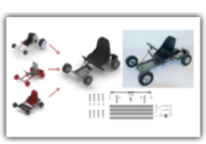
- We can still allow the user some control and design intelligent tools
- Three attempts to allow more interactive tools:
  - Modeling from Photographs
  - Modeling by (Part) Examples
  - Customization of Models



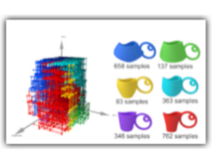




Tao Chen, Zhe Zhu, Ariel Shamir, Shi-Min Hu, Daniel Cohen-Or
3-Sweep: Extracting Editable Objects from a Single Photo
ACM Transactions on Graphics, Volume 32, Number 6, (SIGGRAPH Asia Conference Proceedings), Article 195, 2013
BibTeX More »



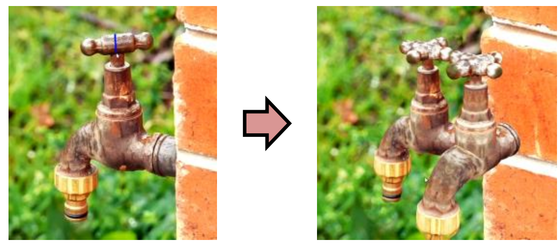
Adriana Schulz, Ariel Shamir, David Levin, Pitchaya Sitthi-Amorn, Wojciech Matusik
Design and Fabrication by Example
ACM Transactions on Graphics, Volume 33, Number 4, (SIGGRAPH Conference Proceedings), Article 62, 2014
BibTeX More »



Maria Shugrina, Ariel Shamir, Wojciech Matusik
Fab Forms: Customizable Objects for Fabrication with Validity and Geometry Caching
ACM Transactions on Graphics, Volume 34, Number 4, (SIGGRAPH Conference Proceedings), Article No. 100, 2015
BibTeX More »

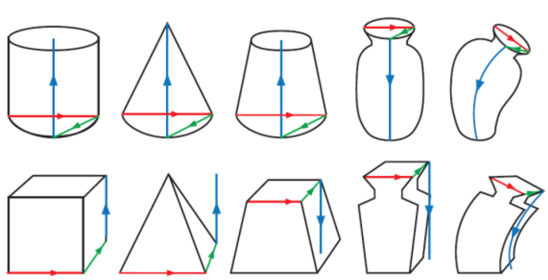
3Sweep Motivations

- Modeling from an image is challenging for automatic computer algorithms
- It is a challenge for humans
- Can we combine forces?



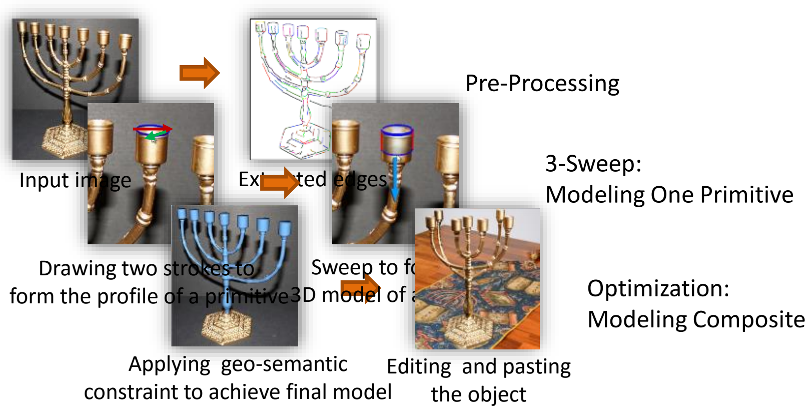
3-Sweep: Image Based Object Modeling

- A simple intuitive gesture to define 3D primitives using 3 mouse sweeps:



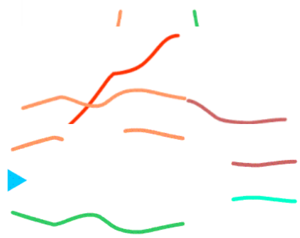
Modeling One Primitive

3Sweep Overview

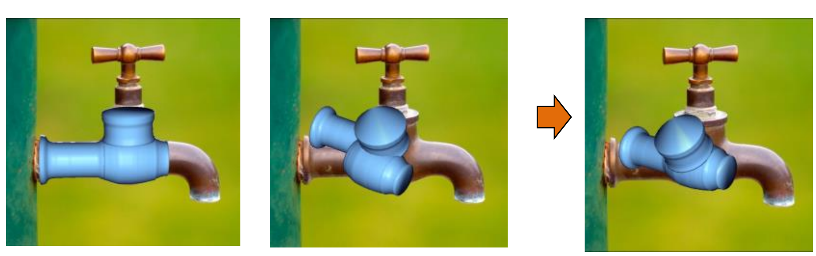


Behind the Scene: Outline Snapping Rules

- Prefer the outline that is parallel to the 3rd stroke
- Stick to the same outline, jump to the one with minimal angle change if necessary
- Use symmetry anc … outline
- Fit to uniform o … se diameters smoothing (assumption: th … lly).

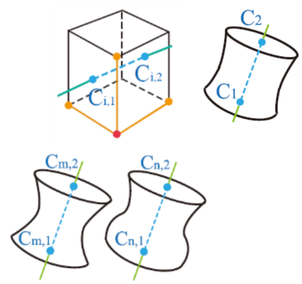


Behind the Scene: Geo-Semantic Constraints



Expert Knowledge: Geo-Semantic Constraints

- Defined in terms of major axes of the primitives.
- Support six constraint types:
    - parallelism
    - orthogonality
    - collinear anchors
    - overlapping anchors
    - coplanar anchors
    - coplanar axes

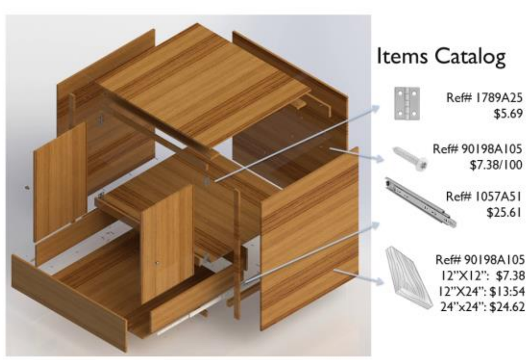


$$(\mathbf{C}_{m,1} - \mathbf{C}_{m,2}) \times (\mathbf{C}_{n,1} - \mathbf{C}_{n,2}) = 0$$

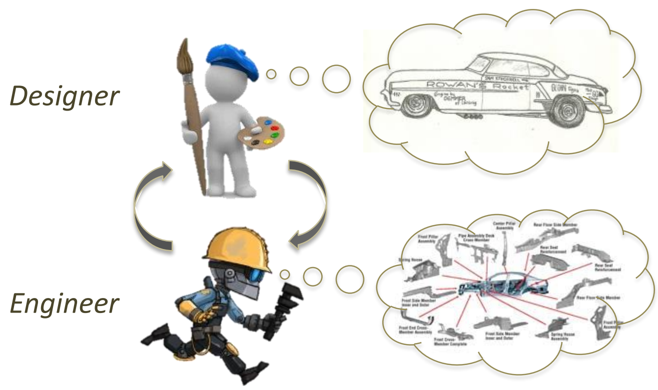
Modeling Session

Virtual vs. Real

Many Parts (~300)

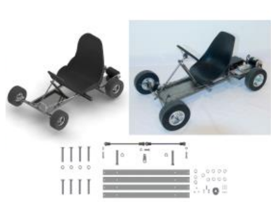


The Design for Fabrication Process



Fabrication by Example Motivation

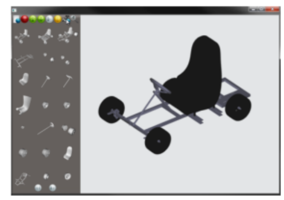
- Designing objects that can be really fabricated:
  - Requires many small details
  - Includes how to connect parts
  - Involves materials, physics…



Key Idea: Database of Example

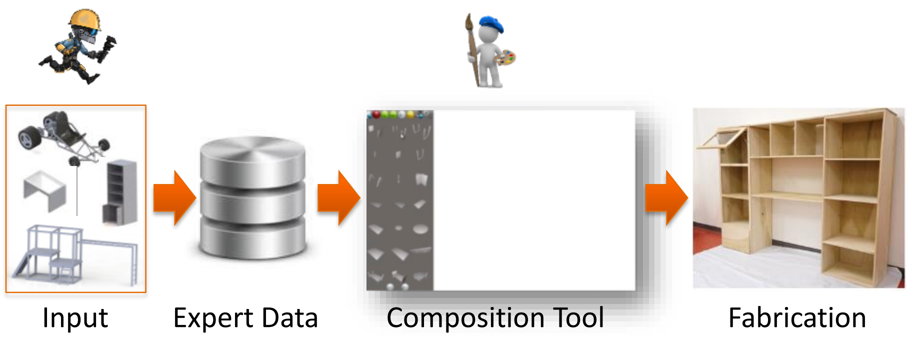
hierarchical parametric objects (templates)

Modeling System

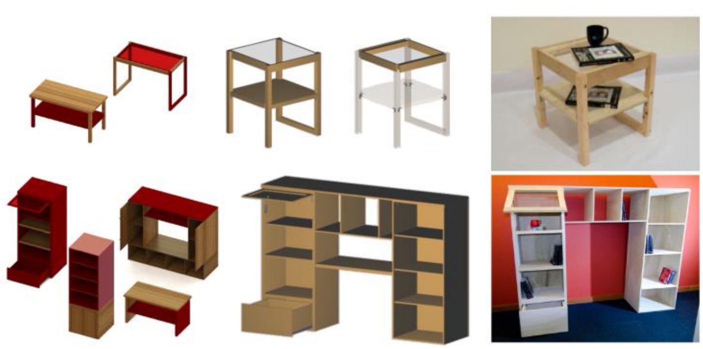


Modeling Session

Approach

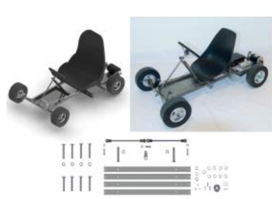


Examples



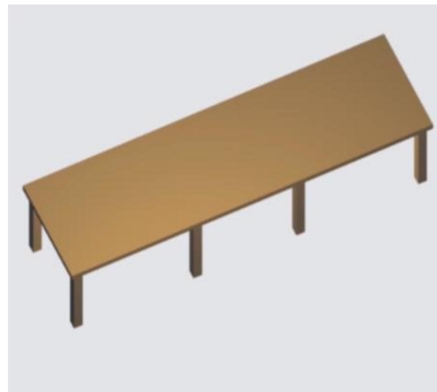
Customizable Models: Parameters & Constraints

Part Based Modeling

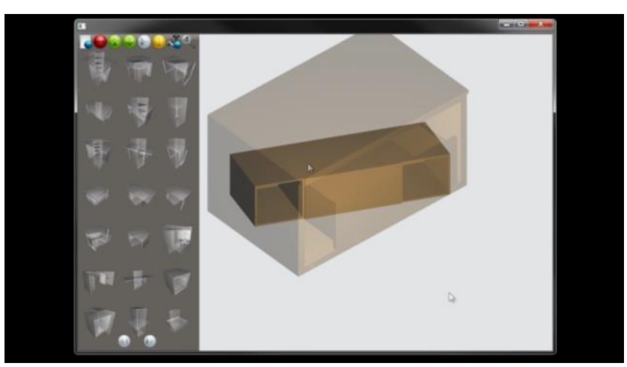


Snapping

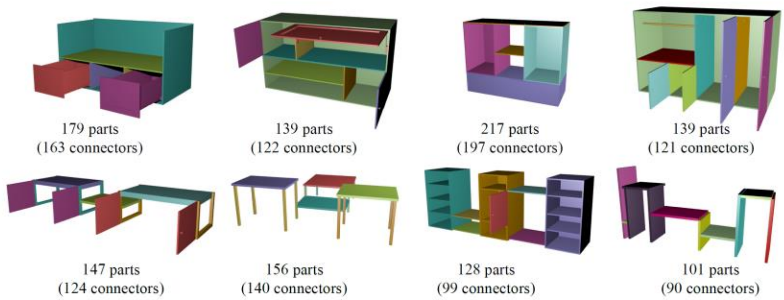
- User interaction
- Preserve alignment constraints



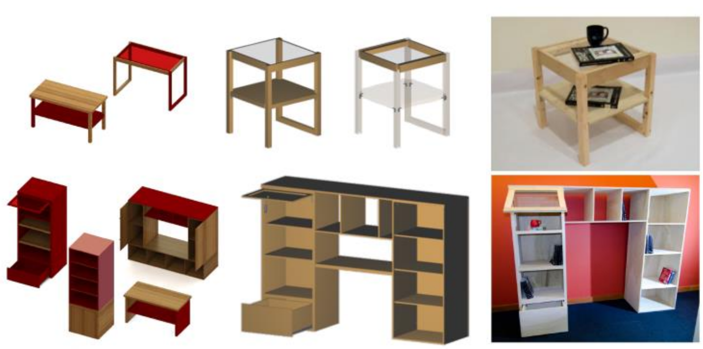
Connectors



Examples

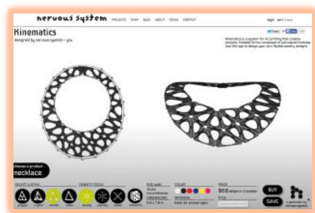


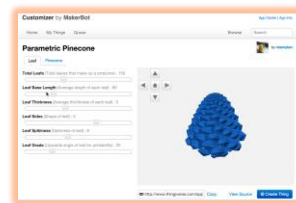
Examples



Customization

- Instead of the user involved in modeling – design customizable objects and allow the user to modify them before fabrication

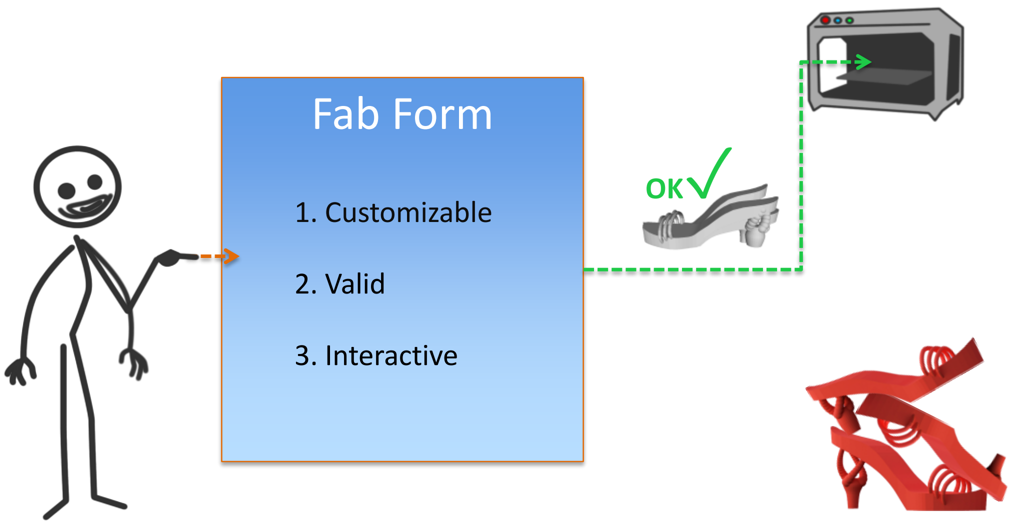




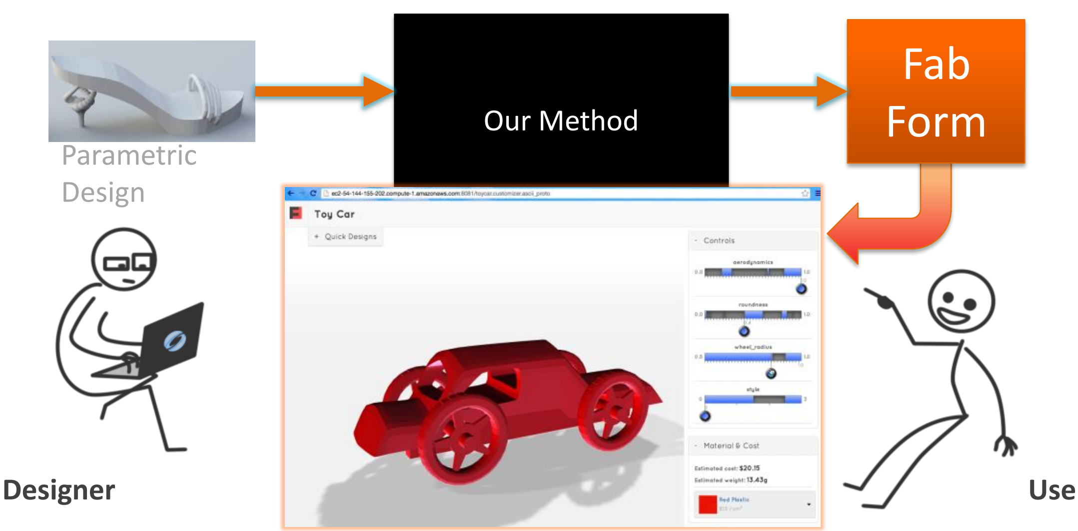
Difficulties

- Which parameters to expose?
- It takes time to compute after change of parameters
- Changing parameters may break the design in various ways:
  - Geometrical (self intersections, invalid boundary, holes)
  - Physical (too thin, unstable, un-printable)

Fab Forms



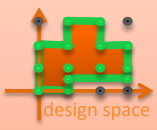
Overview



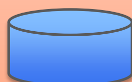
Fab Form Implementation

Fab Form Implementation


Parametric Design



Valid Regions of the Design Space


Geometry Cache

Fab Form Requirements

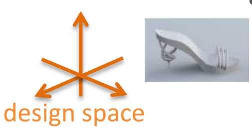
✓ 1. Customizable

✓ 2. Valid

✓ 3. Interactive

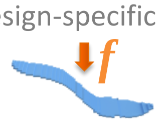
Inputs and Outputs

1. Parametric Design



2. Automatic Tests

- Printability analysis
- Design-specific tests

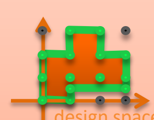


[Doubilet et al. '84, Wu '94, Stava et al. '12, Zhou et al. '13]

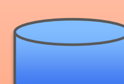
Precomputation →

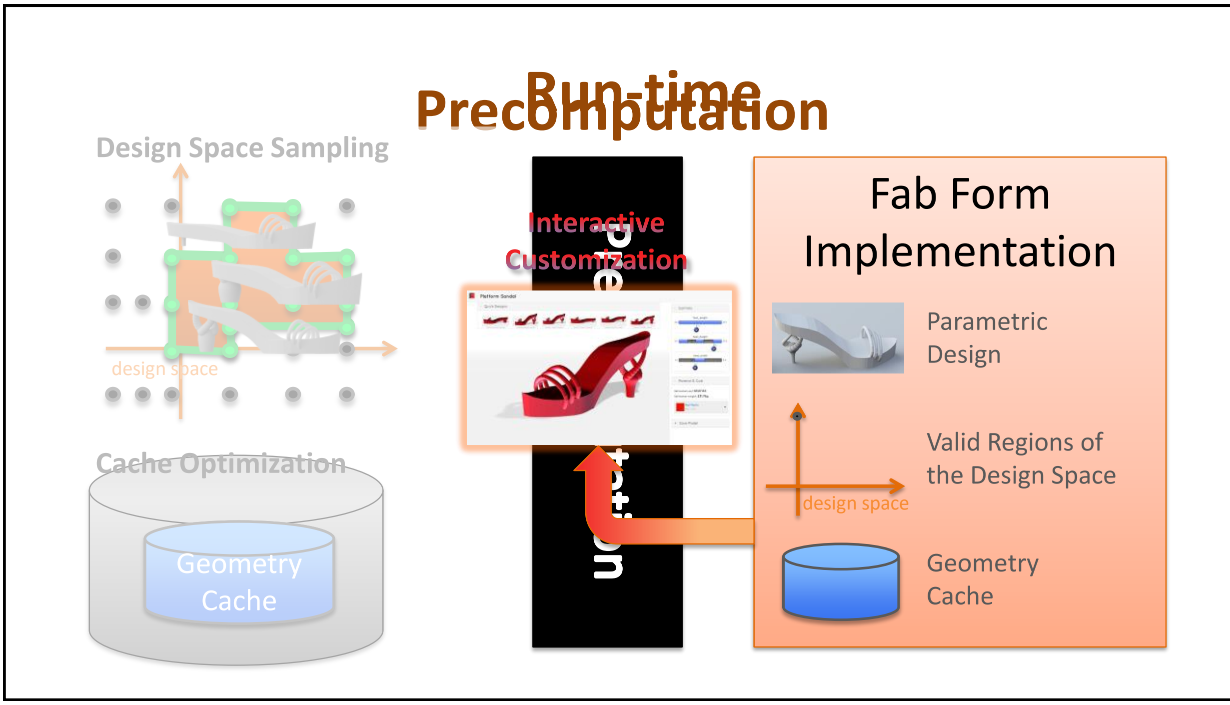
Fab Form Implementation


Parametric Design



Valid Regions of the Design Space


Geometry Cache



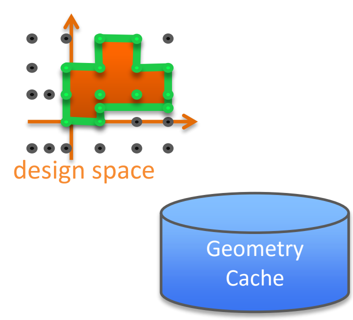
Design Space Sampling

Sampling objectives:

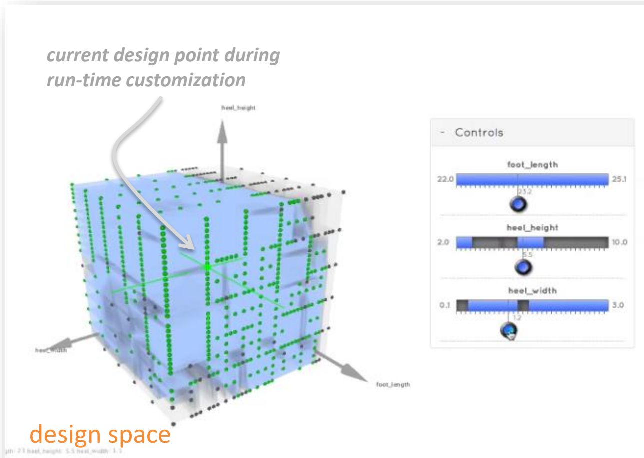
- approximate the valid region
- populate geometry cache

Intuition:

- sample more where geometry changes
- sample more where validity changes



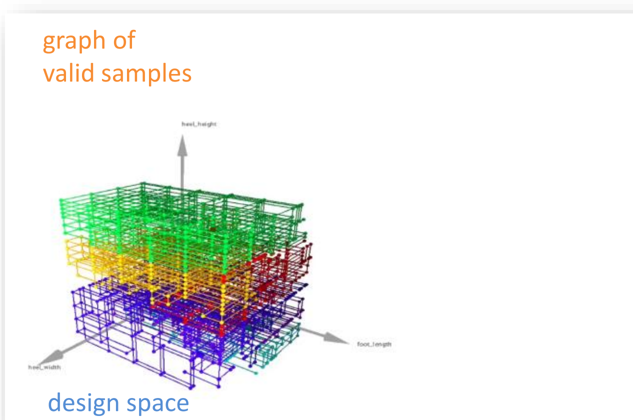
Using the Valid Region



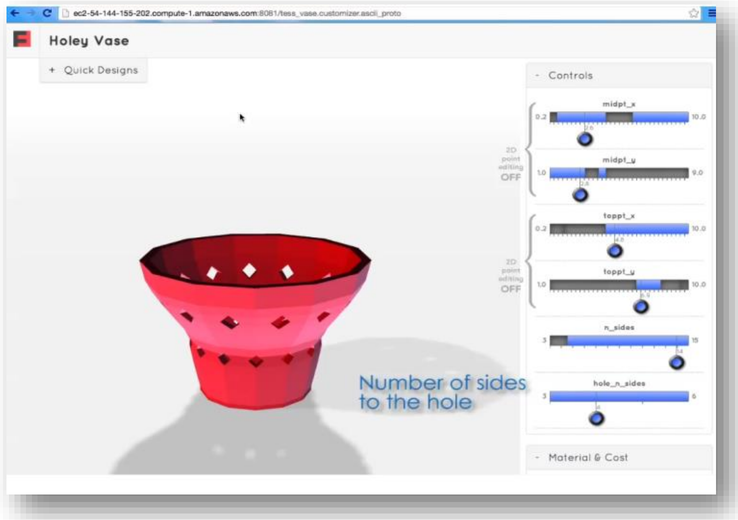
Non-convex, non-contiguous regions difficult to navigate with sliders alone.

[Marks et al. '97, Talton et al. '09, Shapira et al. '09, Koyama et al. '14]

Design Exploration Points



Using Design Exploration Points



Summary

- 3D Modeling for the physical world involves additional challenges : Geometric and Physical Analysis
- Three points of views need to work together for effective modeling:

Designer

Engineer

User

Summary

- 3D Modeling for the physical world involves additional challenges: Geometric and Physical Analysis
- Three points of views need to work together for effective modeling: Designer, Engineer, User
- **Inverse modeling**: mostly changes existing models to fit certain specification
- **Interactive modeling**: still very difficult for novices – need for intelligent tools to assist