Nanoquiz

• go to shoutkey.com/quartz
• 3 minutes (timer in the upper right)
• closed book
• closed notes
• no talking
• no email/FB/IM
• be a good person
• make your mother proud
1. Choose all statements that are true:
A. Functionally Graded Materials can be modeled using voxels
B. OpenFab is a tool for direct specification
C. 3D Printers can only use one material for a given print
D. Rasterization is step in a modern graphics pipeline
Spec2Fab

A Reducer-Tuner Model for Translating Specifications to 3D Prints
Desai Chen, David I.W. Levin, Piotr Didyk, Pitchaya Sitthi-amorn, Wojciech Matusik

MIT CSAIL
Any Questions About Projects

• ??
Important Deadlines!

- Mid-Project Review **April 24**
- Final Presentation and Project Due **May 15**
Plan For Today

- Introduction to Functional Specification
- Example 1: Subsurface scattering
- Example 2: Goal-based Caustics
- Spec2Fab: The Details
Computational Fabrication
Computational Fabrication

Direct Specification
(Last Lecture !)

Functional Specification
Computational Fabrication

Direct Specification
(Last Lecture !)

Functional Specification

f
Functional Specification

Spec2Fab Translation

Printable Object

Functional Specification
Spec2Fab Translation

Assign Material → Simulate → Compare to Goal → Good? → Print

Simulation

Goal
Spec2Fab Translation

Assign Material ➔ Simulate ➔ Compare to Goal ➔ Good? ➔ Print

Simulation

Goal
Spec2Fab Translation

Try all per-voxel material combinations
Naïve Spec2Fab Translation

Try all per-voxel material combinations
Naïve Spec2Fab Translation

Try all per-voxel material combinations
Naïve Spec2Fab Translation

Try all per-voxel material combinations
Naïve Spec2Fab Translation

Try all per-voxel material combinations
Naïve Spec2Fab Translation

Try all per-voxel material combinations
Naïve Spec2Fab Translation
Try all per-voxel material combinations

Number of combinations
2 inch cube at 300 dpi
3 materials

$3 \times 600 \times 3 = \text{Monstrosity}$
Naïve Spec2Fab Translation

- Assign Material
- Simulate
- Compare to Goal
- Good?
- Print
Naïve Spec2Fab Translation

1. Reduced Parameters
2. Simulate
3. Compare to Goal
4. Good?
5. Print
Spec2Fab Translation

- Reduced Parameters
- Optimize
- Simulate
- Compare to Goal
Spec2Fab Translation for Subsurface Scattering

[Hašan et al., 2010]
What is Subsurface Scattering?

- Light penetrates a surface and is scattered multiple times inside the object and then is emitted.
What is Subsurface Scattering

Light Goes In!

Bounces around in here

Light Comes Out!
Materials with Subsurface Scattering
Materials with Subsurface Scattering

Photo by: cliff1066™  
http://www.flickr.com/photos/nostri-imago/3380241354/  

Hands photo by: Josep Ma. Rosell  
http://www.flickr.com/photos/batega/1865482908/  

Peppers photo by: david.nikonvscanon  
http://www.flickr.com/photos/nikonvscanon/474277210/
Applications

Food industry

Interior decorations
Quantifying Reflection – BRDF

• Bidirectional Reflectance Distribution Function
• Ratio of light coming from one direction that gets reflected in another direction
  – **Pure reflection, assumes no light scatters into the material**
• Focuses on angular aspects, not spatial variation of the material
• How many dimensions?
BRDF $f_r$

- Bidirectional Reflectance Distribution Function
  - 4D: 2 angles for each direction
  - $\text{BRDF} = f_r(\theta_i, \phi_i; \theta_o, \phi_o)$
  - Or just two unit vectors:
    $\text{BRDF} = f_r(l, v)$
    - $l =$ light direction
    - $v =$ view direction
BRDF $f_r$

- Bidirectional Reflectance Distribution Function
  - 4D: 2 angles for each direction
  - $BRDF = f_r (\theta_i, \phi_i; \theta_o, \phi_o)$
  - Or just two unit vectors:
    $BRDF = f_r (l, v)$
    - $l = \text{light direction}$
    - $v = \text{view direction}$
  - The BRDF is aligned with the surface; the vectors $l$ and $v$ must be in a local coordinate system
For a fixed incoming direction, view dependence is a 2D spherical function.
Scattering

- BRDFs don’t account for scattering
- We use an augmented model
- Use a BSSRDF – Bidirectional subsurface reflectance distribution functions
- Accounts for the fact that light striking an object may emerge at a different place
BSSRDF Parameterization

- Bidirectional surface scattering reflectance distribution function
  \[ S(\vec{x}_i, \vec{\omega}_i, \vec{x}_o, \vec{\omega}_o) \]

- 8D Function
BSSRDF Parameterization

- Subsurface scattering dominated by multiple scattering
  \[ S(\vec{x}_i, \vec{x}_o) \]
- 4D function
BSSRDF Parameterization

- Subsurface scattering for a homogenous material
  \[ S(\|\vec{x}_o - \vec{x}_i\|) = S(r) \]

- 1D function
BSSRDF Representation

- Scattering in a Homogeneous Slab
  - 1D Reflection Profile $R(r)$
  - 1D Transmission Profile $T(r)$
Reflection Profile Measurement

Sample

Support

Digital camera

Mirror

Digital projector
Reflection Profile Measurement

![Reflection Profile Image]

![Distance vs. Reflection Profile Graph]

Distance \( (r) \) vs. Reflection Profile
Transmission Profile Measurement

- LED flashlight
- Sample
- Support
- tape with pin hole
- diffusing plastic slab
- Digital camera
Building Complexity from Base Materials

Option 1
Arbitrary assignment of materials to volume elements

Option 2
Stacking homogeneous layers
Approach Review

Base Materials

Measurement

Material Library

Simulation and Search

Volumetric Model

Printing

Output

Target Material

Measurement Factorization

Factored BSSRDF
Spec2Fab Translation for Hašan et al.
Spec2Fab Translation for Hašan et al.
Spec2Fab Translation for Hašan et al.
Spec2Fab Translation for Hašan et al.

Goal: scattering profile

Columns + Layers → Scattering Profile

Branch and Bound → Curve Comparison

light intensity vs. distance
Spec2Fab Translation for Hašan et al.

Goal: scattering profile
Spec2Fab Translation for Hašan et al.

Goal: scattering profile

Simulation

Columns + Layers

Scattering Profile

Branch and Bound

Curve Comparison

Goal:

Simulating distance for light intensity.

Goal: scattering profile

Light intensity vs distance graph.
Spec2Fab Translation for Hašan et al.

Columns + Layers

Scattering Profile

Branch and Bound

Curve Comparison

Simulation

light intensity

distance

Goal: scattering profile

light intensity

distance

Goal: scattering profile
Spec2Fab Translation for Hašan et al.

Goal: scattering profile
Spec2Fab Translation for Hašan et al.

Goal: scattering profile

light intensity

distance
Results
Results
Spec2Fab Translation for Papas et al.

Light source

[Papas et al., 2011]
Goal-Based Caustics
Spec2Fab Translation for Papas et al.
Spec2Fab Translation for Papas et al.
Similar: The Magic Lens
And something new
Spec2Fab in Computer Graphics

[Bermano et al., 2012] [Papas et al., 2011] [Weyrich et al., 2009] [Finckh et al., 2010] [Dong et al., 2010] [Bickel et al., 2010] [Hašan et al., 2010] [Papas et al., 2012] [Baran et al., 2012] [Bickel et al., 2012] [Bermano et al., 2012] [Papas et al., 2011]

Reduced Parameters
Simulation
Optimization
Comparison
Spec2Fab in Computer Graphics

[Prévost et al., 2013]

[Skouras et al., 2013]
Spec2Fab in Computer Graphics

We’ll discuss this in detail next lecture!

[Prévost et al., 2013]

[Skouras et al., 2013]
Key Observations

• Spec2Fab processes use a similar structure
Optimization Returns!

Continuous

This point can move smoothly

Discrete

Choose from discrete points in parameter space
We can go anywhere

"Feasible Space"

"Infeasible Space"

Optimization Returns!

We can go anywhere

"Feasible Space"

"Infeasible Space"

Unconstrained

Constrained
Key Observations

• Spec2Fab processes use a similar structure
A Simulation Example

- **Pseudocode:**
  - Zero all arrays
  - For each triangle, \( t \)
    - \( m \leftarrow \text{density of triangle } \times \text{area} \)
    - Compute \( F \)
    - Compute \( \epsilon = \frac{1}{2} (F^T F - I) \)
    - Compute \( \sigma = \psi (\epsilon) \)
    - For each edge, \( e \), in \( t \)
      - \( \text{fe} \leftarrow \sigma \) \( n \) \( l \)
      - \( \text{f[end point 0]} += 0.5 \times \text{fe} \)
      - \( \text{f[end point 1]} += 0.5 \times \text{fe} \)
    - End
  - For each vertex, \( v \), in \( t \)
    - \( m[v] += m/3 \)
  - End
  - End
  - ...
Key Observations

• Spec2Fab processes use a similar structure
• Small set of common components
Key Observations

• Spec2Fab processes use a similar structure
• Small set of common components

Branch and Bound
Linear Solver
QP
Simulated Annealing
SPSA

Reduced Parameters

Simulation

Optimization

Comparison

Subsurface Scattering
Caustics
Shadows
Deformation

Image Distances
Mesh Distances
Curve Distances
Key Observations

• Spec2Fab processes use a similar structure
• Small set of common components
What is Spec2Fab

• A unified model for Spec2Fab translation
  – Modular
  – Extensible
  – Geometry Independent
  – Device Independent
Common Components

- Reduced Parameters
- Simulate
- Compare to goal
- Optimization
- Branch and Bound
- Linear Solver
- QP
- Simulated Annealing
- SPSA
- Subsurface Scattering
- Caustics
- Shadows
- Deformation
- Image Distances
- Mesh Distances
- Curve Distances
Common Components

Reducer Tree

Tuner Network
Our Solution

Reducer Tree

- Hierarchical
- Parameter reduction
- Non-overlapping division
Reducer Tree

- Internal Nodes
  - Spatial Partition

- Leaf Nodes
  - Material Assignment
Reducer Node: Spatial Partition
Reducer Node

- **Internal Nodes**
  - Spatial Partition
  - Stratum
  - Column
  - Plane
  - Spline
  - Voxel

- **Leaf Nodes**
  - Material Assignment
  - Material
  - Void
  - Foam
  - Layer
Our Solution

• Reducer Tree
  – Parameter reduction
  – Hierarchical
  – Non-overlapping division

[Hašan et al., 2010]
Reducer Tree

Input Shape

Stratum

Column

Material

[Hašan et al., 2010]

Layer

Layer

Layer

Layer

Layer

Layer

Layer

Layer
Spec2Fab: Subsurface scattering

[Hašan et al., 2010]

[Dong et al., 2010]
Spec2Fab: Caustics

[Weyrich et al., 2009]  [Papas et al., 2011]
Spec2Fab: Refraction

[Finckh et al., 2010]

[Papas et al., 2012]
Spec2Fab: Shadows

[Baran et al., 2012]  [Bermano et al., 2012]  [Mitra and Pauly, 2009]
Shadow Art

Niloy J. Mitra
IIT Delhi / KAUST

Mark Pauly
ETH Zurich
Spec2Fab: Mechanical

[Bickel et al., 2010]

[Prévost et al., 2013]
Reducer Tree

Query material
Reducer Tree

• Updating local coordinates
Reducer Tree

- Updating local coordinates
- Geometry independence
Reducer Tree

• Updating local coordinates
• Geometry independence
Reducer Tree

Reduced parameters

Input Shape

Stratum (thickness)

Column

Stratum

Material

Material (IDs)

Column (width, height)

Material

Material

Material

Material
Reducer Tree

Reduced parameters

Input
Shape

Stratum (thickness)

Column

Material

Column (width, height)

Material (IDs)

Material

Material

Material
Reducer Tree

Reduced parameters

Input Shape

Stratum (thickness)

Column (width, height)

Material

Material (IDs)
Reducer Tree

- Reduced parameters
  - Column (width, height)
  - Stratum (thickness)
- Input Shape
  - Stratum
    - Material
      - Material (IDs)
Reducer Tree

Reduced parameters

Input Shape

Stratum (thickness)

Column

Column (width, height)

Material

Material (IDs)

Material

Material

Material
Reducer Tree

Reduced parameters

Column (width, height)

Stratum (thickness)

Input Shape

Material (IDs)

Material

Material

Material
Reducer Tree

Reduced parameters

Input Shape

Stratum (thickness)

Column

Stratum

Material

Material (IDs)

Column (width, height)

Material

Material

...
Tuning the Reducer Tree
Tuning the Reducer Tree

- **Input Shape**
- **Stratum**
- **Column (width, height)**
- **Material**
- **Material (IDs)**
- **Material (thickness)**

Diagram showing the relationships between **Tuner**, **Column**, and various types of **Material**.
Tuning the Reducer Tree

- Collect tunable parameters
- Update parameter values

Material

ID

Stratum

Column (width, height)

Material (IDs)

Input Shape

Stratum (thickness)

Tuner
Tuner

Reduced Parameters → Simulate → Compare to goal → Optimization

Tuner
Tuner

- Simulation
- Error Metric
- Optimization
Tuner

Input Shape

Material Composition

Reduced Parameters

Layer

Layer

... Layer

Simulation

Error Metric

Optimization
Tuner for Caustics Inspired by Finckh et al., 2010
Tuner for Deformation Inspired by Bickel et al., 2010
Tuner Network

Optimize each node independently

Stratum (thickness)

Column (width, height)

Material (IDs)

Material
Material
...
Material

Tuner
Tuner
...
Tuner
Tuner Network
Results: Spec2Fab for Texture

Goal

Print

Input Shape

Stratum

Column

Material

Material

... Material

Tuner

Tuner

... Tuner
Spec2Fab for Texture

Goal

Input
Shape

Stratum

Column

Material

Material

Material

...
Spec2Fab for Texture
Spec2Fab for Hašan et al.
Spec2Fab for Hašan et al.

Goal

Print
Spec2Fab for Papas et al.
Spec2Fab for Finckh \textit{et al.}
Spec2Fab for Caustics and Texture

Side view of a slab

Input Shape

Spline

Tuner

Material

Void

Print
Spec2Fab for Caustics and Texture

Side view of a slab
Spec2Fab for Caustics and Texture

Side view of a slab
Spec2Fab for Caustics and Texture

Goal: caustics
Goal: texture

Print

Material
Void

Tuner

Input Shape
Plane
Texture

Spline
Spec2Fab for Deformation and Texture

Goal: deformation

Goal: texture

Input Shape

Tuner

Stratum

Texture

Voxel

Material

Material

... Material

Print
Conclusions

• Spec2Fab: unified model for fabrication algorithms
  – Reducer tree
  – Tuner network
  – Modular, extensible, geometry independent, device independent