Rethinking Texture Mapping

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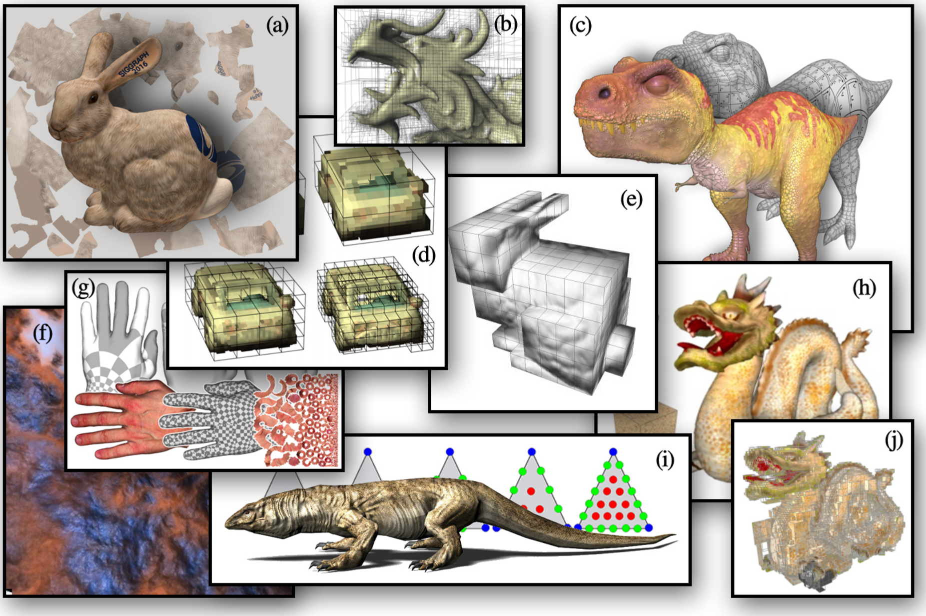

Figure 1: *Examples alternatives to texture mapping: (a) volume-encoded uv-maps [Tarini 2016], (b) octree textures [Lefebvre et al. 2005], (c) Ptex [Burley and Lacewell 2008] (©Walt Disney Animation Studios), (d) brickmaps [Christensen and Batali 2004], (e) polycube-maps [Tarini et al. 2004], (f) gigavoxels [Crassin et al. 2009], (g) invisible seams [Ray et al. 2010], (h) perfect spatial hashing [Lefebvre and Hoppe 2006], (i) mesh colors [Yuksel et al. 2010], and (j) tiletrees [Lefebvre and Dachsbacher 2007].*

ABSTRACT

The intrinsic problems of standard Texture Mapping, regarding UV-maps and seams, are well-known, but often considered unavoidable. In this course we will discuss various radically different ways to rethink texture mapping that have been proposed over decades, each offering different advantages and trade-offs.

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1 INTRODUCTION

In computer graphics, texture mapping is the fundamental means by which high-frequency signals such as diffuse colors, normals, and other shading parameters are defined over 3D surfaces. The principle is to store surface details in 2D high-resolution texture images, and then define a mapping from the 3D surface to the 2D image, assigning a uv coordinate to each mesh vertex. This approach is ubiquitously adopted by virtually all computer graphics applications and implemented on all available graphics hardware, from high-end to smartphone GPUs.

However, texture mapping has a number of fundamental issues. Creating uv-maps is time consuming and involves extensive manual effort. Distortions and seams introduced by mapping complicate texture authoring, filtering, and procedural synthesis. The final result is optimized for a specific mesh and it does not necessarily work through LoDs. Any change to the geometry or the connectivity implies updating the uv-mapping and textures. As a consequence, texture mapping continues to occupy a substantial portion of artist time, which dominates the cost of AAA video game production.

Since the early days of texturing, there has been a constant research effort to alleviate or even bypass traditional texture mapping limitations (Figure 1). Unfortunately, the ubiquitous adoption of texture mapping implies that it is seldom questioned as the method of choice, and both authoring pipelines and rendering engines have been shaped around its intrinsic limitations, thereby making it harder for alternatives to be adopted. Yet, the industry recently started to recognize the advantages of alternative approaches to texture mapping, in particular the Ptex method [Burley and Lacewell 2008] is becoming increasingly popular.

The objective of this course is to make the audience more familiar with such alternative approaches and their advantages and trade-offs regarding versatility, ease of authoring, storage cost, rendering quality and performance, and implementation difficulty. We believe the course to be both timely and necessary: several advances in GPU technologies has made alternative texturing approaches computationally very efficient and the industry has shown a renewed interest in moving beyond texture mapping. Furthermore, the algorithms and data-structure used by some alternative approaches extend beyond texturing, towards solid modeling, volume rendering, and simulations on surfaces (e.g. dynamic texturing).

2 OVERVIEW

We begin with discussing the limitations and strengths of standard 2D texture mapping, which is ubiquitously used for virtually all computer graphics applications. This approach stores UV coordinates as attributes on the vertices of a mesh and they are interpolated inside faces, mapping the surface over one or multiple rasterized texture image(s). Then we explain the criteria we used for evaluating alternative methods to texture mapping.

Perfecting Traditional UV-maps. We present methods that address specific shortcomings of the standard 2D texture mapping approach by carefully using it in specific ways. This Section covers the following techniques:

Invisible seams [Ray et al. 2010] provide a method that aligns the seams on a texel grid in texture space, making them consistent with bilinear filtering, thereby hiding the filtering artifacts near seams that appear with traditional texture mapping.

Seamless toroidal/cylindrical textures [Tarini 2012] avoid vertex duplication at seams and eliminate filtering artifacts near seams for some specific classes of maps.

Seamless texture atlases [Purnomo et al. 2004] produce texture atlases that prevent filtering artifacts near seams. They also support down-sampling for mip-mapping and mesh simplification.

Connectivity-based Representations. These methods use the inherent parameterization of the model, instead of defining a separate parameterization for mapping. The topology of the mesh model is used directly for defining the texture data on each primitive. These approaches substantially improve the texture authoring process, but they require 3D painting tools. This Section covers the following techniques:

Ptex [Burley and Lacewell 2008] is used and promoted by Disney Animation and Pixar studios. It effectively assigns a separate texture map to each quad-shaped faces of a mesh. This structure eliminates the need for defining uv-mapping, and it is primarily designed for quad meshes. Texture filtering across faces is handled by accessing the mesh topology.

Mesh colors [Yuksel et al. 2010] are closely related to p-tex and similarly used in production [Lambert 2015]. Extending the concept of vertex colors with additional samples inside mesh faces and on edges, mesh colors provide a topological dual of p-tex in terms of color sample placement. This provides better support for triangular meshes and correct handling of extraordinary vertices. It also eliminates the need for accessing the topology information during texture filtering.

Mesh color textures [Yuksel 2016] aim to utilize the existing texture filtering hardware on current GPU for sampling/filtering mesh colors. It achieves this by effectively converting mesh colors to a representation similar to standard 2D textures. As a result, the authoring benefits of mesh colors can be used without any visible overhead at render time (as compared to standard 2D textures).

Sparse Volumetric Textures. These techniques associate the texture data directly using the volume embedding the 3D model, bypassing the need of constructing or storing any mapping. A naïve implementation of this approach would require a large space, which would be cubic with the resolution of the sampling. Several countermeasures are adopted to avoid this problem using sparse volumetric data structures. This Section covers the following techniques:

Adaptive texture maps [Kraus and Ertl 2002] provide a GPU-based method for locally adjusting the texture resolution depending on the texture content and adaptive texture boundaries.

Octree textures [Benson and Davis 2002; Lefebvre et al. 2005] encode a volumetric texture using an efficient octree hierarchy that is used for texturing surfaces without the need for a uv-map.

Brick maps [Christensen and Batali 2004] were developed for storing precomputed global illumination in arbitrary scenes. They extend the concept of octree textures by introducing voxel blocks with efficient caching that make them suitable for handling extremely large scenes. An implementation of brick maps is included in the RenderMan software.

Perfect spatial hashing [García et al. 2011; Lefebvre and Hoppe 2006] also provides a volumetric encoding of texture values to efficiently store the color values in a hash table that is accessed using 3D positions of the surface. Construction of the hash functions is time consuming but automatic. Cache coherency is an issue.

Gigavoxels [Crassin et al. 2009] are designed for efficiently rendering large volumetric data sets using a sparse 3D structure for texture storage.

Volume-based Parameterizations. These techniques construct a mapping from the 3D model space to a 2D texture space. This Section covers the following techniques:

TileTrees [Lefebvre and Dachsbacher 2007] also extend octree textures by storing 2D texture tiles on the surfaces of octree nodes. They can efficiently adapt to the given object shape and require much fewer octree levels for representing high-resolution textures.

PolyCube-maps [Tarini et al. 2004] generalize the concept of cube-maps that provides a tighter enclosure for the target surface. They are GPU-friendly and produce a cut-free parameterization over a polycube surface that can be used for texturing.

Volume-encoded uv-maps [Tarini 2016] define the uv-mapping as a trilinearly interpolated low-resolution 3D lattice, instead of a per-vertex assignment of uv coordinates. This requires only basic HW support and is almost as efficient as plain texture mapping, and supports different tessellations, including LoDs, but does not bypass the need for of uv-map creation.

The course will provide the details of the alternative methods to texture mapping listed above, discuss their similarities and differences, and present their advantages and limitations. Our aim is to provide the knowledge needed for determining the best candidate for replacing texture mapping for any application, which we expect to be different based on the constraints of the application.

3 TEXTURE MAPPING

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Rethinking Texture Mapping

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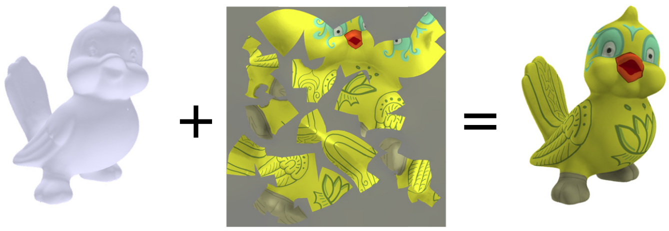
Texture Mapping

- Texture mapping is the fundamental means by which high-frequency details (such as color) are defined on surfaces.



Digital Surface

Densely Sampled Signal
("Texture")

Detail-rich renderings

Texture Mapping

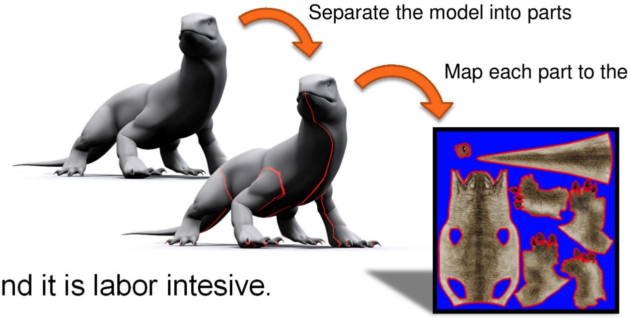
- Requires defining a mapping from the model space to the texture space.

Model Space

Texture Space

Texture Mapping

- Mapping introduces seams

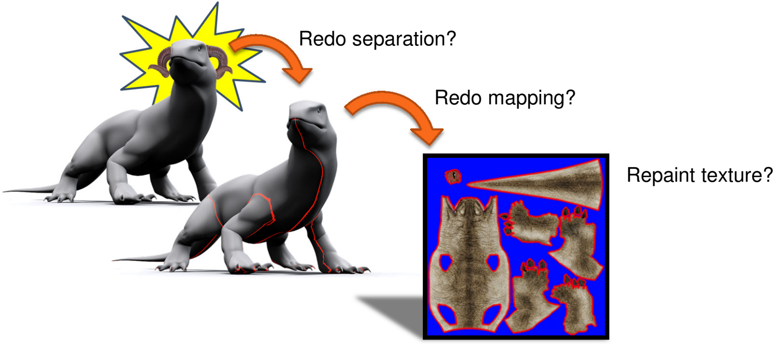

Separate the model into parts

Map each part to the texture space

and it is labor intesive.

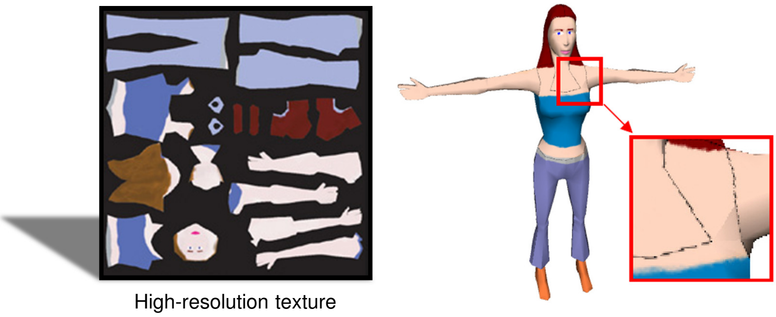
Texture Mapping

- Model editing after texture painting is problematic.



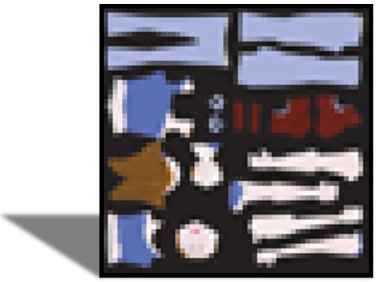
Texture Mapping

- Seams introduce filtering artifacts.

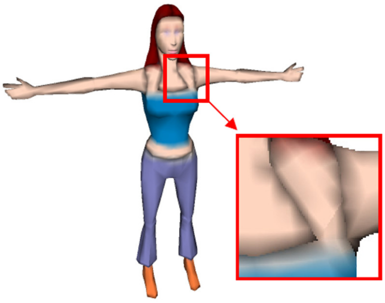

High-resolution texture

Texture Mapping

- Artifacts are more pronounced at higher mip-map levels.



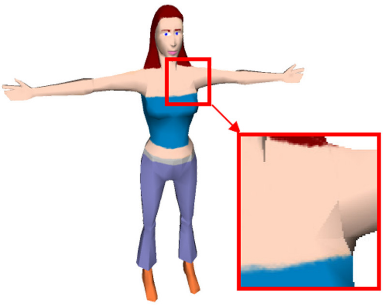
Low-resolution mip-map level



Texture Mapping

- Carefully painting around seams can hide artifacts, but not completely eliminate them.

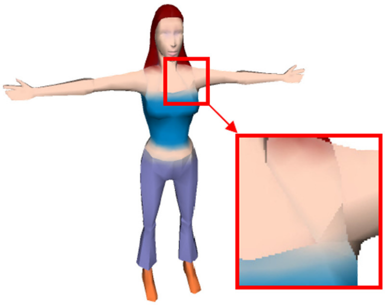
High-resolution texture



Texture Mapping

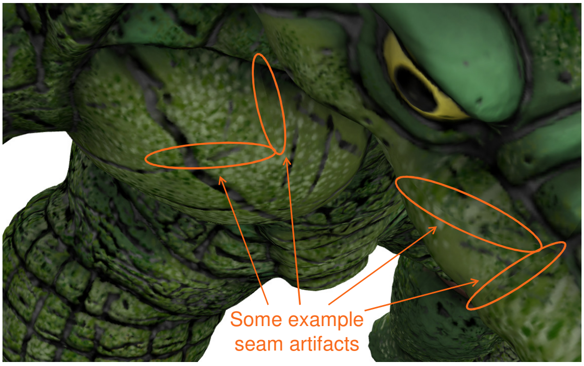
- Seam artifacts still appear in mip-map levels.

Low-resolution mip-map level



Texture Mapping

- Without mip-mapping, seam artifacts can be mostly hidden.



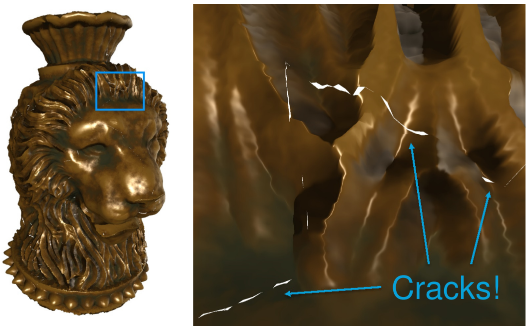
Some example seam artifacts

Texture Mapping

Displacement maps

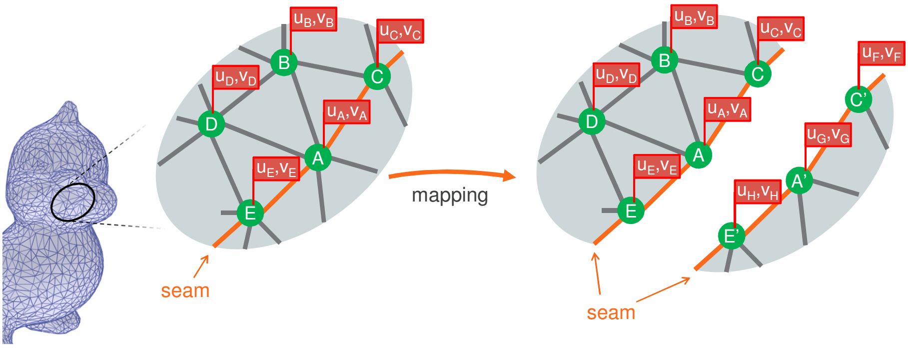
- Seams cause cracks!

  Eliminating these cracks requires carefully adjusting the mapping, so that the texture filtering results on either side of the seam are identical, which is often impossible with standard 2D textures.



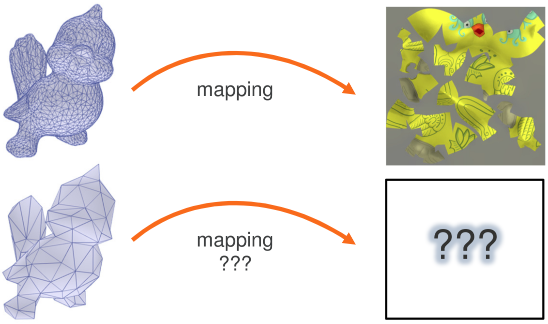
Texture Mapping

- Vertex attributes along seams must be duplicated



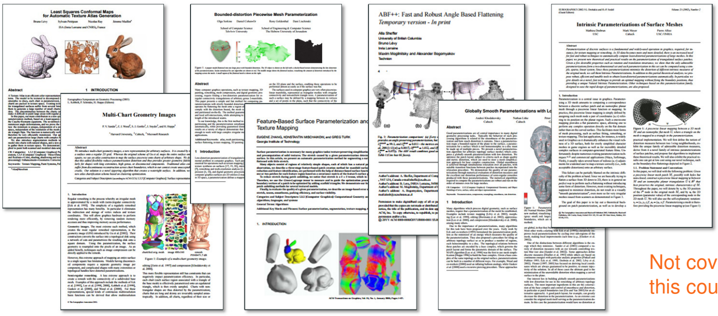
Texture Mapping

- Mapping is mesh dependent



Attempts to automatize mapping

- While there are methods for automated mapping, in practice mapping requires substantial manual effort.



Least Squares Conformal Maps for Automatic Texture Atlas Generation

Bounded-distortion Piecewise Mesh Parameterization

ABF++: Fast and Robust Angle Based Flattening

Intrinsic Parameterizations of Surface Meshes

Multi-Chart Geometry Images

Feature-Based Surface Parameterization and Texture Mapping

Globally Smooth Parameterizations with L

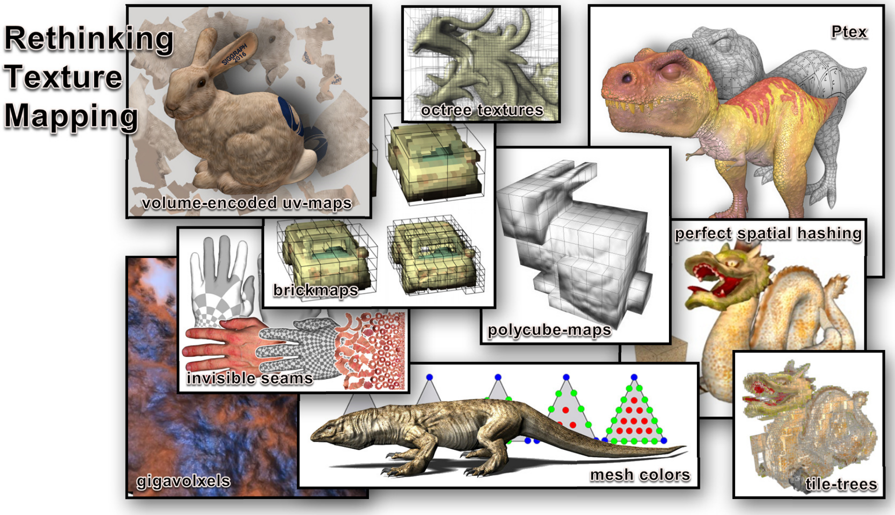
Not covered in this course

Problems of Texture Mapping

- Defining mapping is labor-intensive
  - *Cannot be fully automated*
  - *Time consuming even for experts*
  - *Beyond the ability of most non-experts*
- Local resolution adjustment is problematic
  - *Locally changing the resolution requires (partial) remapping*
- Model editing after texture painting is problematic
  - *Changes to the model may require (partial) remapping*
- Seams introduce artifacts
  - *Inconsistencies on either side of a seam reveal the seam and cause cracks in displacement mapping*

Problems of Texture Mapping (cont.)

- Additional storage cost
  - *UV mapping data per vertex*
  - *Duplicated vertex data along seams*
  - *Wasted space due to imperfect packing and borders around seams*
- Mesh dependency
  - *It is not easy to use the same texture on a different tessellation of the same model, which would be particularly useful for LoD.*



Course Outline

9:00 Introduction: Limitations of Traditional Texture Mapping

9:15 Perfecting Traditional UV-maps
Invisible Seams, Seamless Toroidal/Cylindrical Textures, Seamless Texture Atlases

9:30 Connectivity-based Representations
Ptex, mesh colors, mesh color textures

9:45 Sparse Volumetric Textures
Adaptive Texture Maps, Octree/N^3 Textures, Brick Maps, Perfect Spatial Hashing, Gigavoxels

10:05 Volume-based Parameterizations
Tiletrees, PolyCube Maps, Volume-encoded UV-Maps

10:20 Conclusion and Questions

Evaluation

- Applicability
  Supported surface representations or model types
- Usability
  Permitted mapping/painting operations
- Quality
  Texture filtering quality
- Performance
  Storage, access, and computation overhead
- Implementation
  Development effort needed

Evaluation: Applicability

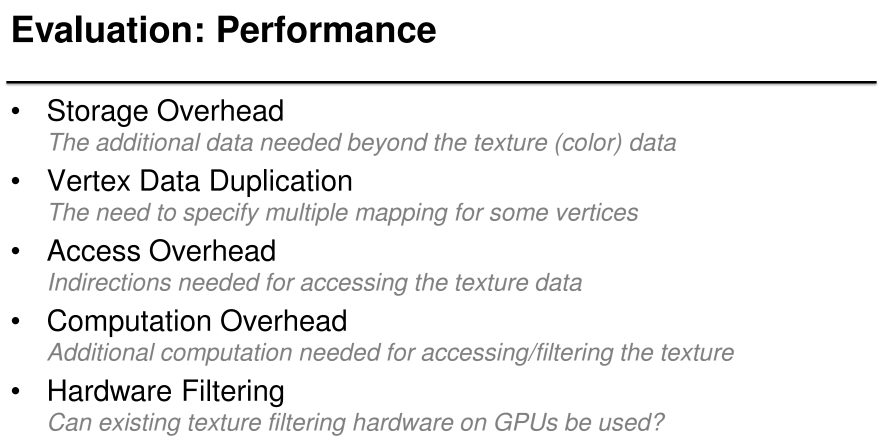
- Meshes
- Point Clouds
- Implicit Surfaces
- Shape/Topology Limits
  Any restrictions on the surface shape or mesh topology
- Subdivisions
  Higher resolution tessellations of a mesh
- Tessellation Independence
  Lower resolution tessellations and/or remeshing support

Evaluation: Usability

- Automated Mapping
  Can a "good" mapping to the texture space be automatically generated?
- Manual Mapping
  Manually generating/editing the mapping to the texture space
- Model Editing after Painting
  Changing the model topology after mapping/painting
- Resolution Readjustment
  Changing the local texture resolution after the texture is (partially) painted
- Texture Repetition
  The ability to use the same texture (color) data on multiple parts of the model
- 2D Image Representation
  Support for editing the texture using existing 2D image editing/painting tools

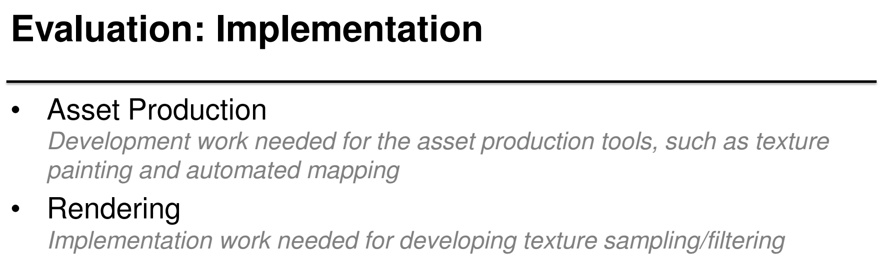
Evaluation: Quality

- Magnification Filtering
  Bilinear filtering quality
- Minification Filtering
  Trilinear filtering (Mip-map) quality
- Anisotropic Filtering
  Anisotropic filtering quality



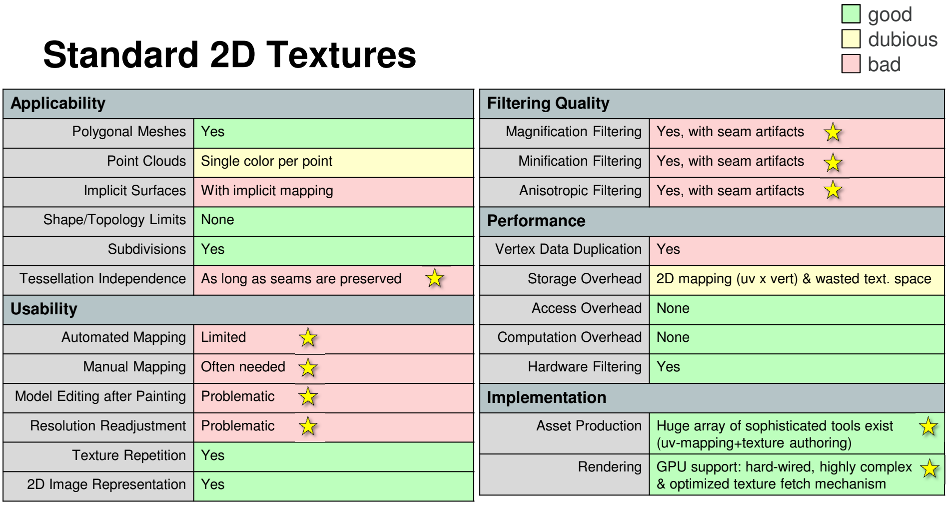
Evaluation: Performance

- Storage Overhead
  The additional data needed beyond the texture (color) data
- Vertex Data Duplication
  The need to specify multiple mapping for some vertices
- Access Overhead
  Indirections needed for accessing the texture data
- Computation Overhead
  Additional computation needed for accessing/filtering the texture
- Hardware Filtering
  Can existing texture filtering hardware on GPUs be used?



Evaluation: Implementation

- Asset Production
  Development work needed for the asset production tools, such as texture painting and automated mapping
- Rendering
  Implementation work needed for developing texture sampling/filtering



Standard 2D Textures

🟩 good
🟨 dubious
🟥 bad

Applicability	
Polygonal Meshes	Yes
Point Clouds	Single color per point
Implicit Surfaces	With implicit mapping
Shape/Topology Limits	None
Subdivisions	Yes
Tessellation Independence	As long as seams are preserved ☆
Usability	
Automated Mapping	Limited ☆
Manual Mapping	Often needed ☆
Model Editing after Painting	Problematic ☆
Resolution Readjustment	Problematic ☆
Texture Repetition	Yes
2D Image Representation	Yes

Filtering Quality	
Magnification Filtering	Yes, with seam artifacts ☆
Minification Filtering	Yes, with seam artifacts ☆
Anisotropic Filtering	Yes, with seam artifacts ☆
Performance	
Vertex Data Duplication	Yes
Storage Overhead	2D mapping (uv x vert) & wasted text. space
Access Overhead	None
Computation Overhead	None
Hardware Filtering	Yes
Implementation	
Asset Production	Huge array of sophisticated tools exist (uv-mapping+texture authoring) ☆
Rendering	GPU support: hard-wired, highly complex & optimized texture fetch mechanism ☆

4 PERFECTING TRADITIONAL UV-MAPS

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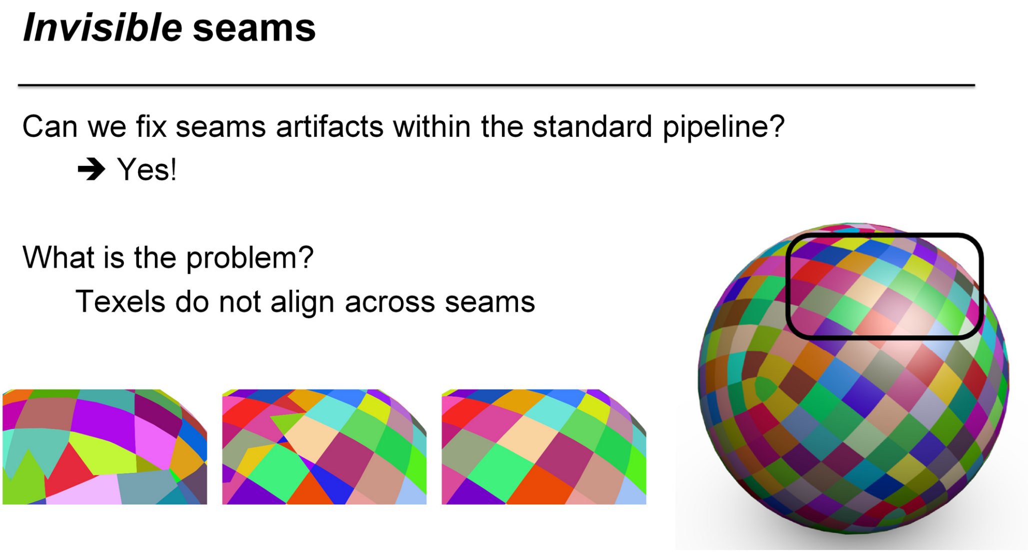
Perfecting Traditional UV-Maps

RETHINKING TEXTURE MAPPING

4.1 Invisible seams



Invisible seams

Can we fix seams artifacts within the standard pipeline?

➔ Yes!

What is the problem?

Texels do not align across seams

It might seem this is hopeless, but invisible seams is actually a technique that can remove the seams entirely while not changing the standard pipeline at all.

Let’s have a closer look at the issue to understand the core idea.

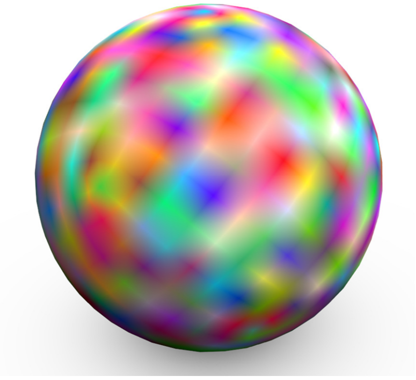
This is a sphere textured with a typical approach. The rendering uses nearest mode to clearly see the big texels.
If we look closely where the charts meet on the surface, you will see that not only the colors disagree, but the grids are misaligned. This is why even if we tried to match the colors, the seam would still be there (unless, again, if the color is constant!).

Now, this second case shows you a very special mapping, called grid preserving. As you can see the colors mismatch but now the texel grid on both sides do match! This is revealed by the fact that the square boundaries perfectly align across the seam.

This third case shows what happens if you now match the colors on both sides. No seam! It is still there in fact, but because everything matches perfectly now – colors and alignment – the rendering perfectly agrees on both sides, making the seam effectively *invisible*.

Invisible seams

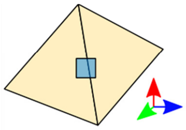
Given this carefully prepared UV map …



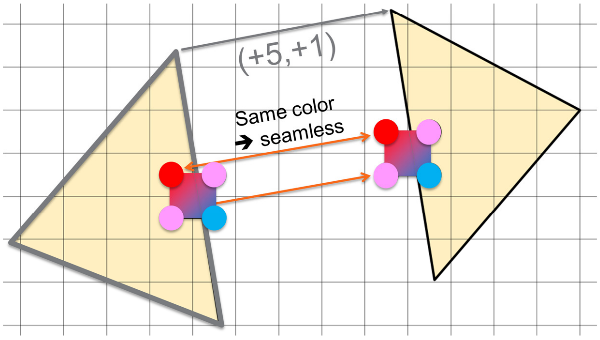
No rendering seam!!

And here is what happens through bilinear filtering. Still no visible seam!

Grid preserving mapping



Mesh surface and interpolation cell



Grid preserving UV map

Here at the top left you can see two triangles along the surface. The blue square is an interpolation cell, that is, four texels in between which we'd like to interpolate color.

Now, the center drawing is the texture space. This particular mapping is grid preserving. What does this mean? It mean that I can take this green triangle on the left and translate it next to the right one. When doing this, we note two important things: First, the edges align perfectly, and second the translation is an integer vector, here (+5,+1).

This is why the interpolation cells actually perfectly align on both sides of the seam. Note that in general, a grid preserving mapping also allows (and requires) 90 degree rotations.

Because the interpolation cells match, it is enough to make sure the colors are the same. On one side the colors are inside the triangle, so we can expect these have been painted along the surface. On the right side they are outside of the triangle, so we can simply duplicate the color there.

After doing this, you can now see the interpolation cells. Note the dashed line, which is the edge of the triangles. The colors match perfectly along it, this is why no seam will be visible.

Pipeline

1- Compute grid preserving parameterization [difficult]

2- Regroup triangles in charts [easy]

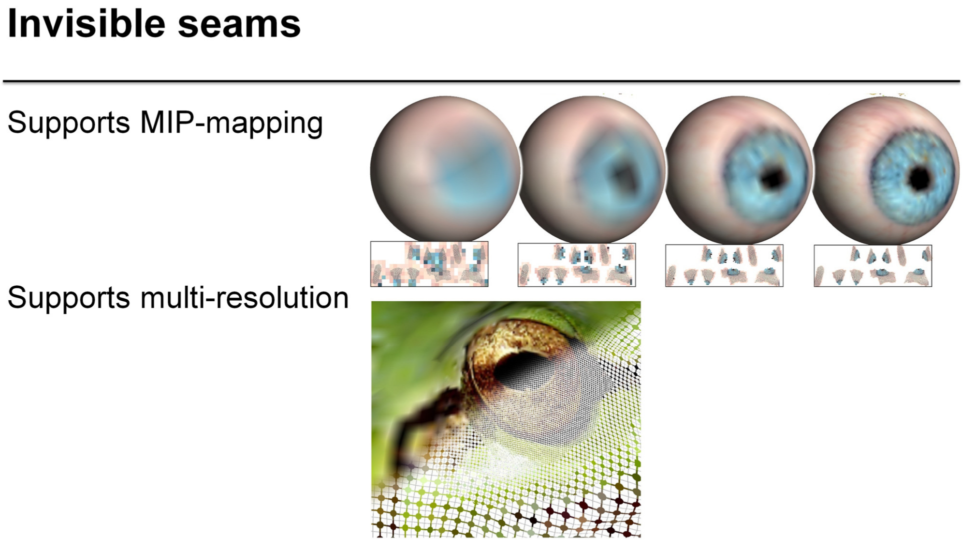
3- Propagate color constraints [some difficulties]

So what invisible seams does is to first compute a grid preserving parameterization. This is a difficult problem, directly related to quadrangulation, but there is now quite a state of the art with good methods out there. Nevertheless, this is not something easy to implement, especially in a robust manner.
Once this is done, the approach regroups triangles into charts, and then propagates colors so that interpolation across boundaries match exactly – as I have just described.

Invisible seams

Example of seamless UV map

Here is how it looks. On the left the rendering, on the right the automatically generated grid preserving mapping. You can see that the charts are not painting-friendly, which is one limitation.



Invisible seams

Supports MIP-mapping

Supports multi-resolution

There are additional benefits. MIP-mapping is supported, as well as multi-resolution, which comes from the fact that the grids align.

🟩 good
🟨 dubious
🟥 bad

Invisible Seams

Applicability	
Polygonal Meshes	🟩 Yes
Point Clouds	🟥 No
Implicit Surfaces	🟥 No
Shape/Topology Limits	🟥 Depends on parameterization robustness
Subdivisions	🟩 Yes
Tessellation Independence	🟥 If seams are preserved
Usability	
Automated Mapping	🟥 Limited
Manual Mapping	🟥 Nearly impossible
Model Editing after Painting	🟥 Problematic
Resolution Readjustment	🟥 Problematic
Texture Repetition	🟩 Yes
2D Image Representation	🟥 Poor

Filtering Quality	
Magnification Filtering	🟩 Yes ☆
Minification Filtering	🟩 Yes ☆
Anisotropic Filtering	🟥 Yes but seams (could be fixed)
Performance	
Vertex Data Duplication	🟥 Yes
Storage Overhead	🟥 2D mapping + wasted space
Access Overhead	🟩 None ☆
Computation Overhead	🟩 None ☆
Hardware Filtering	🟩 Yes ☆
Implementation	
Asset Production	🟥 Automated mapping
Rendering	🟩 Standard pipeline ☆

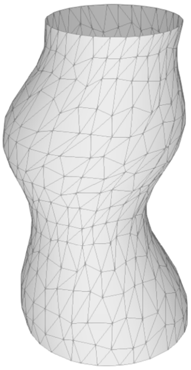
To conclude, invisible seams is a way to make rendering seams truly invisible, that supports MIP-mapping and multi-resolution and is backward compatible with whatever supports texture mapping.
Unfortunately it is quite hard to implement, manual construction of grid preserving mapping is impossible without computational support, and as a consequence painting directly in the texture becomes quite difficult.

4.2 Seamless Toroidal/Cylindrical Textures

Seamless Toroidal/Cylindrical Textures

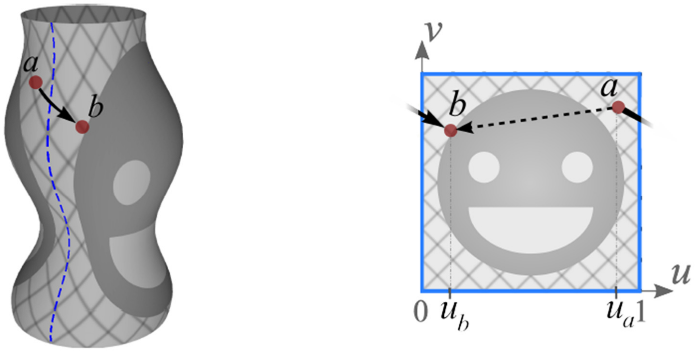
[Tarini 2012]

Task: UV map this!



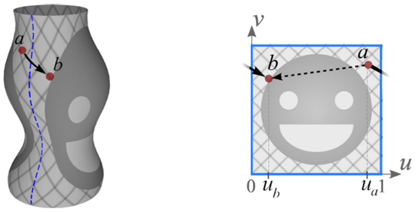
Task: UV map this!

Easy: cylindrical maps

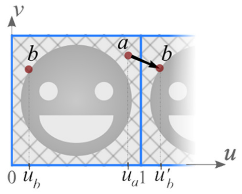


Wrapping Textures

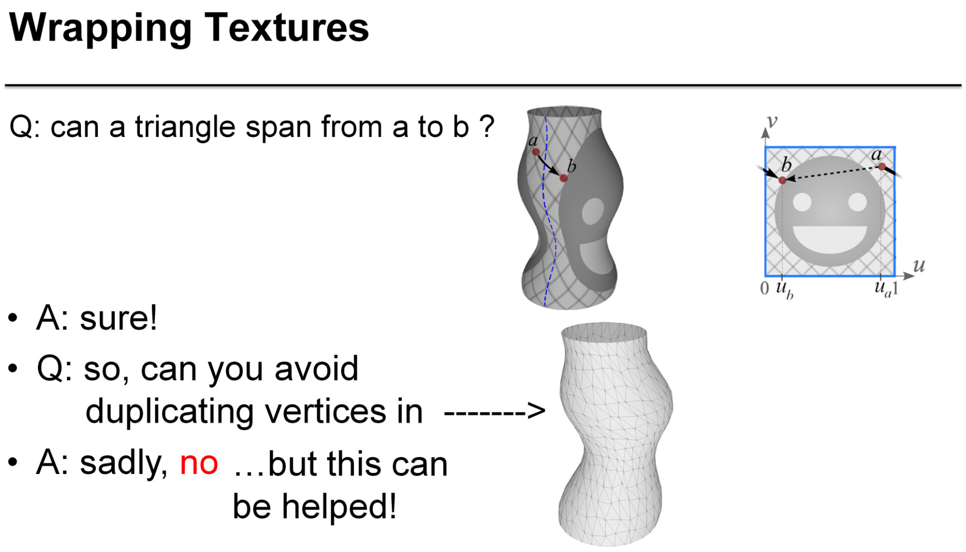
Q: can a triangle span from a to b ?



- A: sure!
  - *a.u* = 0.9
  - *b.u* = ~~0.1~~ = 1.1
  - relay on *wrap*
    texture fetch mechanism



Oldest trick in the book!
Seams: invisible
Built in support in any GPU
Easy HW implementation.
Effortless.
The most common way of having a seam in a texture… which almost doesn't count as a seam!
The perfect UV param (when it applies, which is not too often)



Wrapping Textures

Q: can a triangle span from a to b ?

- A: sure!
- Q: so, can you avoid
  duplicating vertices in ------->
- A: sadly, no …but this can
  be helped!

Almost doesn't count.
You still have to duplicate vertices:
complicate data strcutres.
Hinders procedurality: e.g. you cannot create U coords on the fly.

But, there is a simple little known technique to do this.
See: Cylindrical and toroidal parameterizations without vertex seams M Tarini
Journal of Graphics Tools 16 (3), 144-150
It is a short paper, just use it if it fits your needs.

Take home message

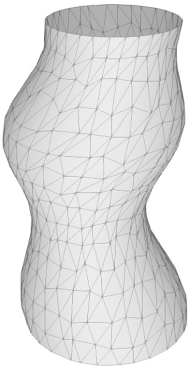
Contrary to common belief,
you don’t really need duplicate vertices in a cylindrical / toroidal map

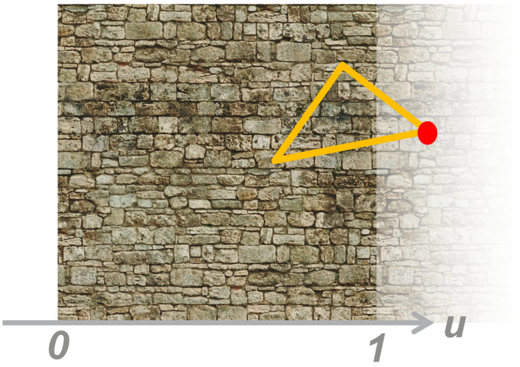
How: *Cylindrical and toroidal parameterizations*
without vertex seams
M Tarini
JGT 2012

Demo at:
http://vcg.isti.cnr.it/~tarini/no-seams/

Let’s see how this work

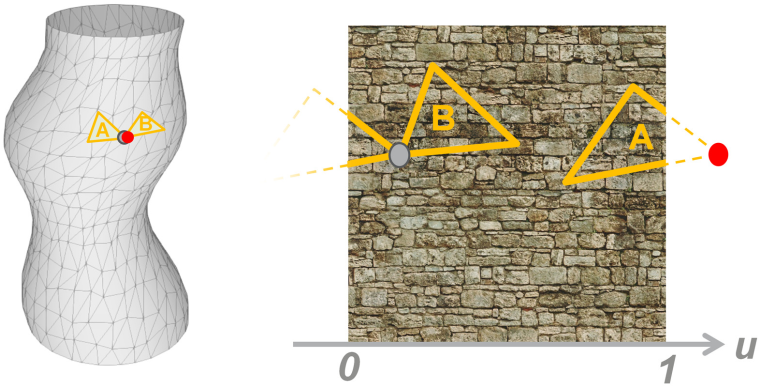
Wrapping Textures





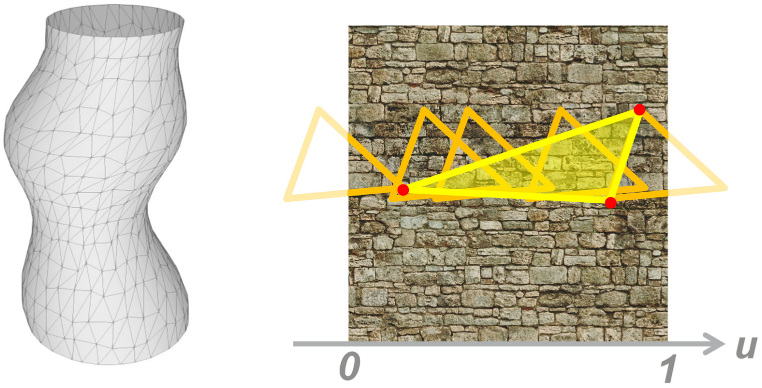
This triangle here needs RED VERTEX to be at 1.1

Wrapping Textures



But this other triangle B here needs the *same* vertex to be at 0.1

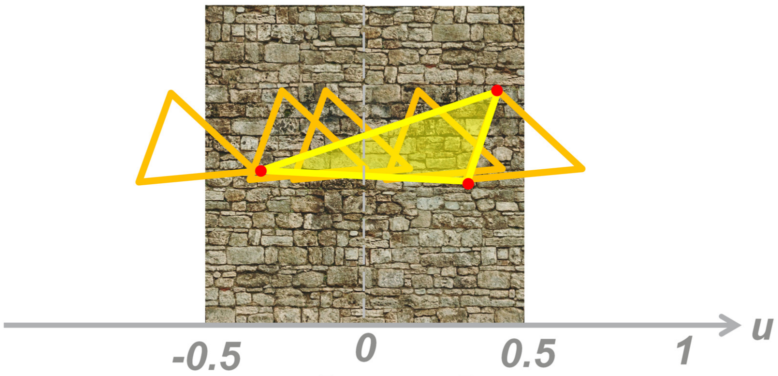
Wrapping Textures



[Animation on slide – doesn't read well on printed slide]
If you used always used U coords in 0..1, any triangle spanning across the left-right seam would get wrong interpolated U values, like here

Wrapping Textures

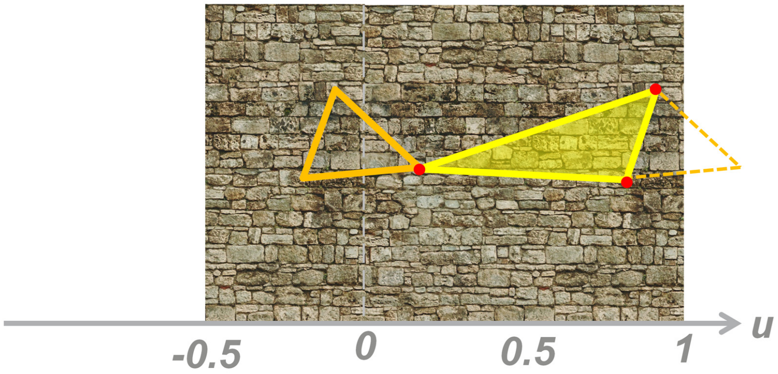
Wrapping Textures



$u_1\ ,\ \ u_2 = [\, u_1 + 0.5 \,] - 0.5$

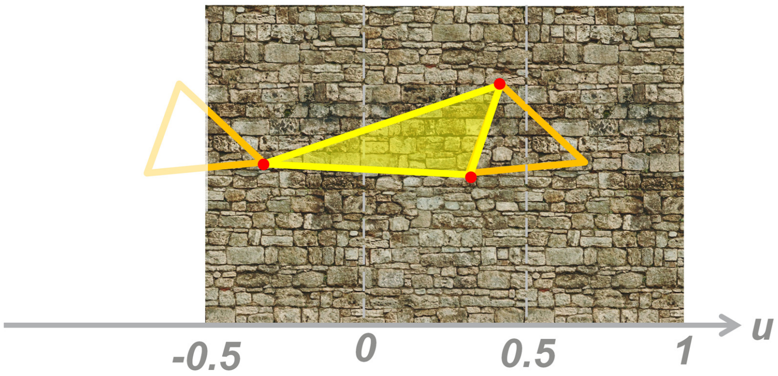
[Animation on slide – doesn't read well on printed slide]
But what if you used this other interval: U inside [-0.5, +0.5].
(it is easy to go from the prev interval to this, with this formula)
Now that triangle now works, thanks to the wrapping built in in the fetch mechanism.
But, now, a triangle spanning the original mid point of the texture gets the wrong interpolated position.

Wrapping Textures

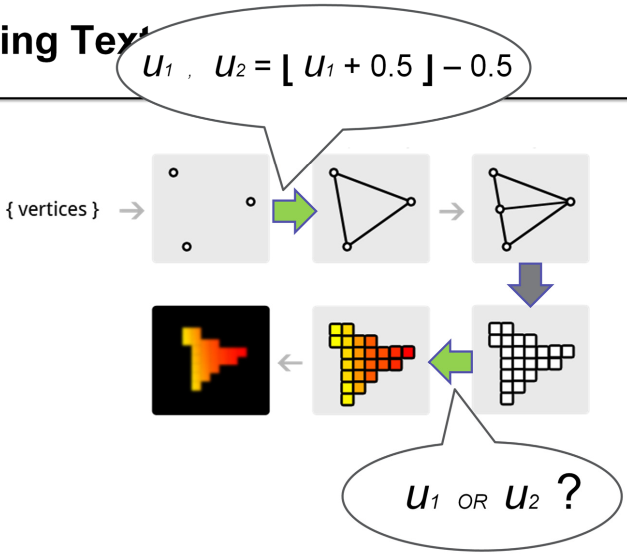


So this triangle requires t

Wrapping Textures



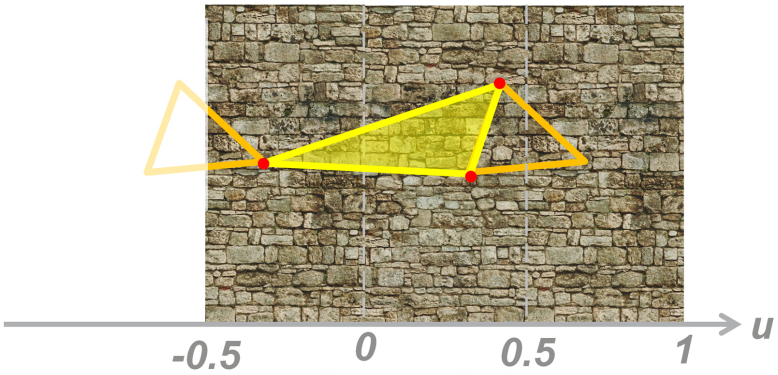
Wrapping Tex



u_1 , $u_2 = \lfloor u_1 + 0.5 \rfloor - 0.5$

u_1 OR u_2 ?

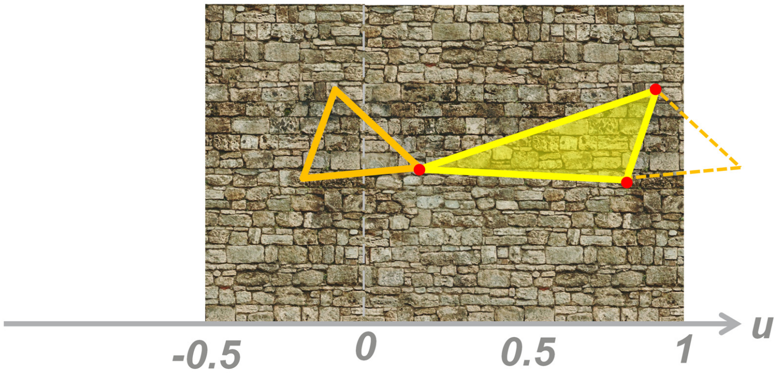
Wrapping Textures



u_1 , $u_2 = \left[\, u_1 + 0.5 \,\right] - 0.5$

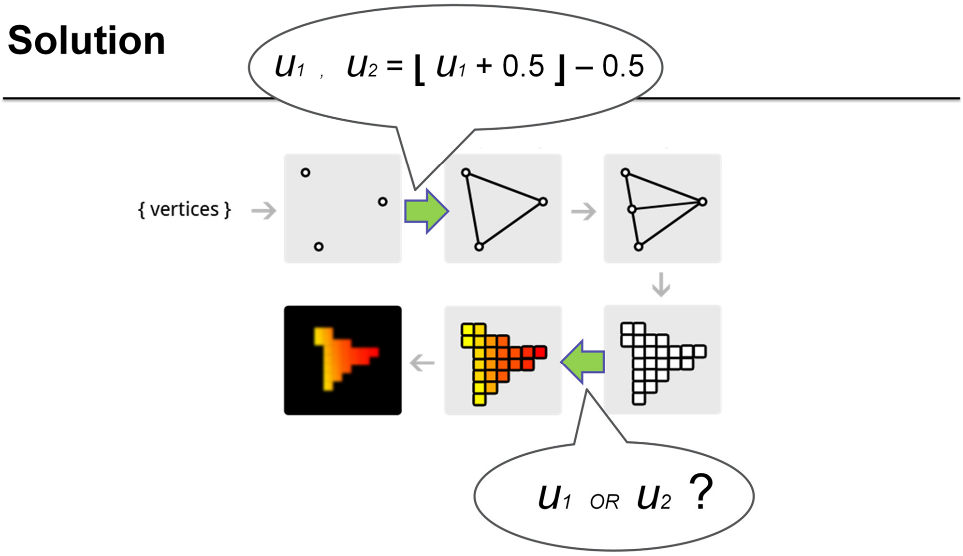
So this triangle needs the original cords u1

Wrapping Textures



$$u_1 \;,\quad u_2 = \left[\, u_1 + 0.5 \,\right] - 0.5$$

but this requires the modified coord u2.
Can we make all happy?



Solution

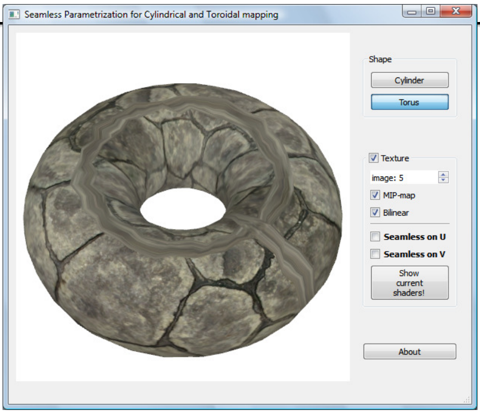
u_1 , $u_2 = \lfloor u_1 + 0.5 \rfloor - 0.5$

u_1 OR u_2 ?

We could use the geometry shader to choose which way to go for each triangle, but the Geom Shader is often very costly. We don't need it!
So here's the trick.
In the vertex shader (first green arrow), you compute u2 from u1.
Both gets interpolated by the rasterizer (vertical arrow).
Last problem: in the fragment shader, you get two (potentially different) values u1 and u2.
We know one is right. The other might be wrong (see the two slides above)
How do you pick the right one?
This is seemingly impossible for the fragment shader to tell…
But: the answer is: it is always the one (u1 or u2) which is travelling less fast in screen space.
The triangle "spanning the texture in the wrong direction" is always the one "taking the longest route".
(this assumes a triangle is never larger than HALF the entire texture space, which is more than reasonable).
So, you want to pick the other one.
You want to pick the u1 or u2 value… which is associated to the smallest (in module) SCREEN SPACE DERIVATIVE.
Recall that

Screen space derivatives!

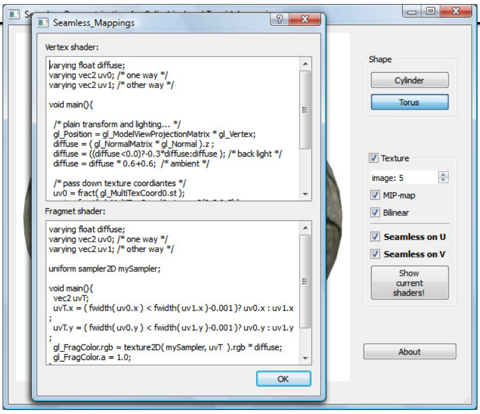
DEMO



☑ Texture
image: 5
☑ MIP-map
☑ Bilinear
☐ **Seamless on U**
☐ **Seamless on V**

Screen space derivatives!

DEMO



Vertex shader:

```
varying float diffuse;
varying vec2 uv0; /* one way */
varying vec2 uv1; /* other way */

void main(){

  /* plain transform and lighting... */
  gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
  diffuse = ( gl_NormalMatrix * gl_Normal ).z ;
  diffuse = ((diffuse<0.0)?-0.3*diffuse:diffuse ); /* back light */
  diffuse = diffuse * 0.6+0.6;  /* ambient */

  /* pass down texture coordiantes */
  uv0 = fract( gl_MultiTexCoord0.st );
```

Fragmet shader:

```
varying float diffuse;
varying vec2 uv0; /* one way */
varying vec2 uv1; /* other way */

uniform sampler2D mySampler;

void main(){
  vec2 uvT;
  uvT.x = ( fwidth( uv0.x ) < fwidth( uv1.x )-0.001 )? uv0.x : uv1.x
;
  uvT.y = ( fwidth( uv0.y ) < fwidth( uv1.y )-0.001 )? uv0.y : uv1.y
;
  gl_FragColor.rgb = texture2D( mySampler, uvT ).rgb * diffuse;
  gl_FragColor.a = 1.0;
```

☑ Texture
image: 5
☑ MIP-map
☑ Bilinear
☑ **Seamless on U**
☑ **Seamless on V**

🟩 good
🟨 dubious
🟥 bad

Seamless Toroidal/Cylindrical Textures

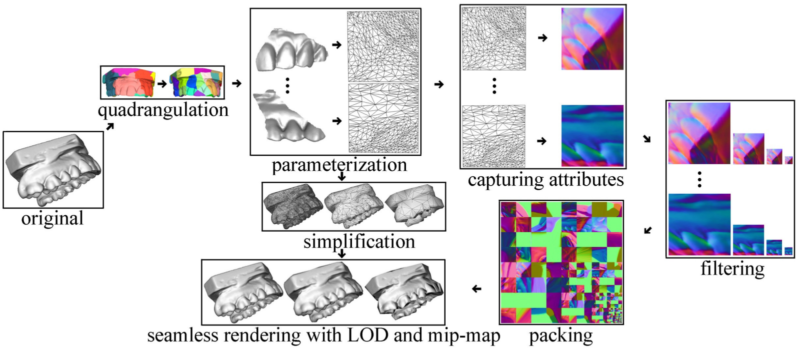
Applicability	
Polygonal Meshes	Quads & triangles
Point Clouds	No
Implicit Surfaces	No
Shape/Topology Limits	**ONLY TORUS/CYLINDER TOPOLOGY**
Subdivisions	Yes
Tessellation Independence	Yes
Usability	
Automated Mapping	Limited, usually easy
Manual Mapping	Not much customizability
Model Editing after Painting	No
Resolution Readjustment	Problematic
Texture Repetition	Yes (multiple rounds around cyl possible)
2D Image Representation	Yes, complete

Filtering Quality	
Magnification Filtering	Yes
Minification Filtering	Yes
Anisotropic Filtering	Yes
Performance	
Vertex Data Duplication	No! ☆
Storage Overhead	2D mapping (uv)
Access Overhead	None
Computation Overhead	Extremely small (1 extra interpolant)
Hardware Filtering	Yes
Implementation	
Asset Production	Automated mapping
Rendering	Simple UV manipulation

4.3 Seamless Texture Atlases

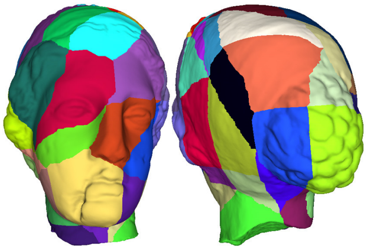
Seamless Texture Atlases

[Purnomo 2004]



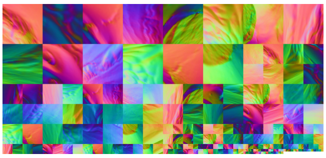
Seamless Texture Atlases

- Begins with quadrangulation
  - Split the input mesh into sets of polygons that are flattened onto square-shaped regions on the uv-map



Seamless Texture Atlases

- The texels for quad regions (charts) are packed into a texture
- The mip-map levels are stored within the same texture

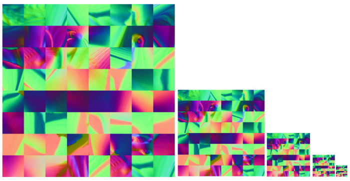


- A lookup table stores locations of each chart for each mip-map level

---

Seamless Texture Atlases

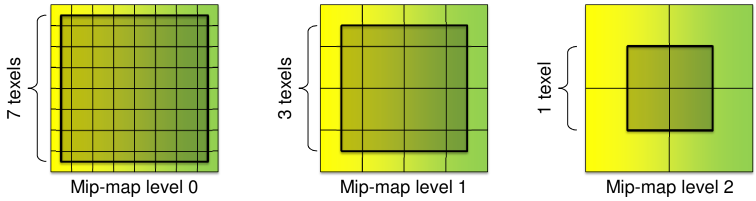
- Alternatively, hardware mip-map storage can be used



- A lookup table stores locations of each chart

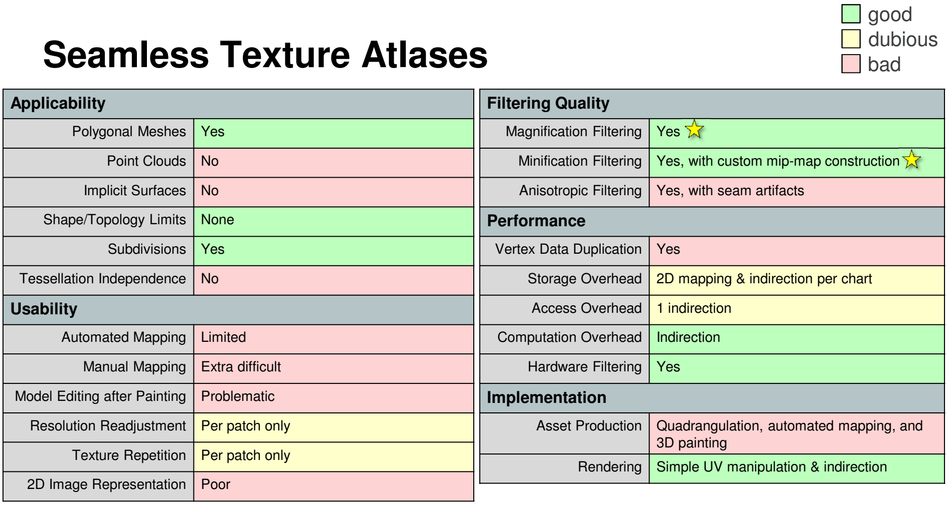
Seamless Texture Atlases

- Half a texel boundary needed around each chart
- Texture coordinates must be scaled according to the texel size of the mip-map level.



Seamless Texture Atlases

- Hardware bilinear filtering
- Indirection using a lookup table
- Requires quadrangulation and automated mapping per chart



🟩 good
🟨 dubious
🟥 bad

Seamless Texture Atlases

Applicability	
Polygonal Meshes	Yes
Point Clouds	No
Implicit Surfaces	No
Shape/Topology Limits	None
Subdivisions	Yes
Tessellation Independence	No
Usability	
Automated Mapping	Limited
Manual Mapping	Extra difficult
Model Editing after Painting	Problematic
Resolution Readjustment	Per patch only
Texture Repetition	Per patch only
2D Image Representation	Poor

Filtering Quality	
Magnification Filtering	Yes ☆
Minification Filtering	Yes, with custom mip-map construction ☆
Anisotropic Filtering	Yes, with seam artifacts
Performance	
Vertex Data Duplication	Yes
Storage Overhead	2D mapping & indirection per chart
Access Overhead	1 indirection
Computation Overhead	Indirection
Hardware Filtering	Yes
Implementation	
Asset Production	Quadrangulation, automated mapping, and 3D painting
Rendering	Simple UV manipulation & indirection

5 CONNECTIVITY-BASED REPRESENTATIONS

30 JULY – 3 AUGUST Los Angeles
SIGGRAPH2017

Connectivity-based Representations

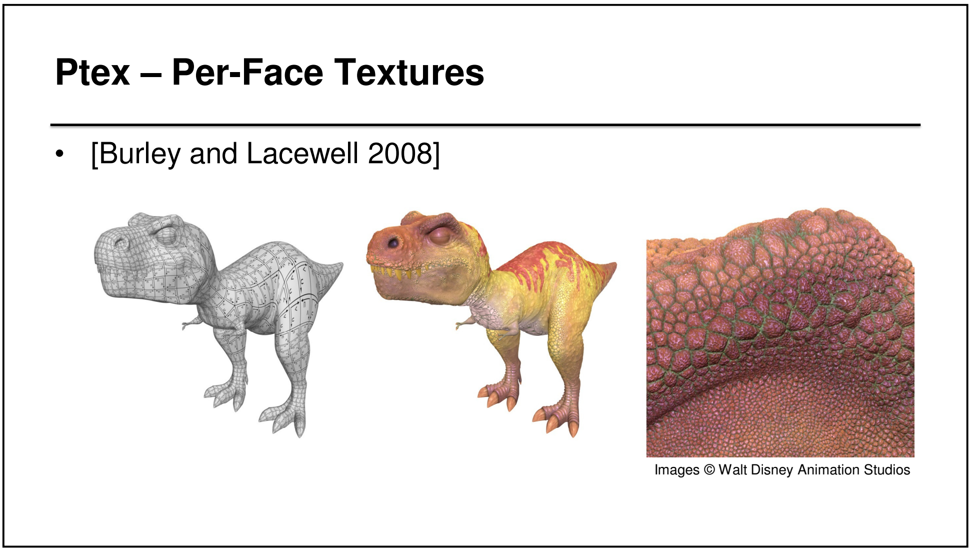
RETHINKING TEXTURE MAPPING

Ptex – Per-Face Textures

- [Burley and Lacewell 2008]

Images © Walt Disney Animation Studios

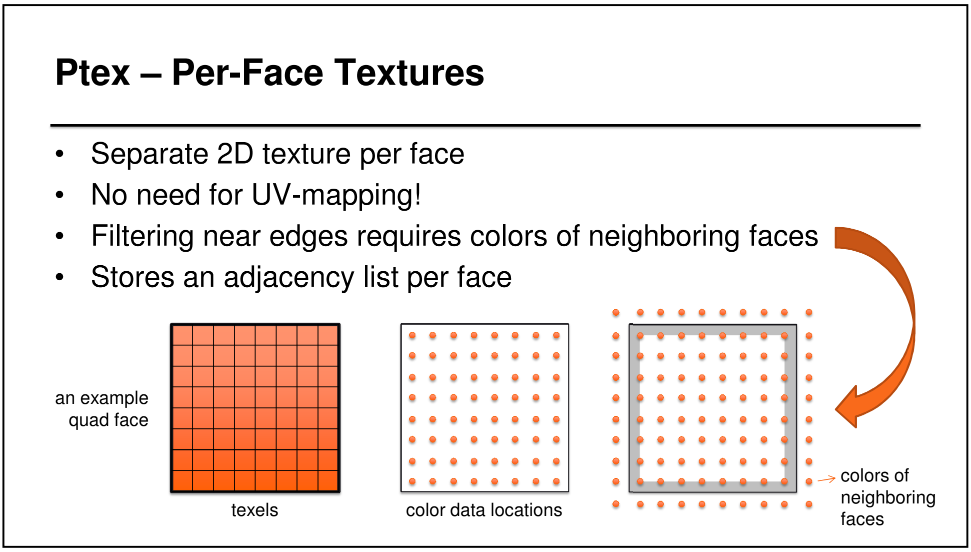
5.1 Ptex



Ptex – Per-Face Textures

- [Burley and Lacewell 2008]

Images © Walt Disney Animation Studios



Ptex – Per-Face Textures

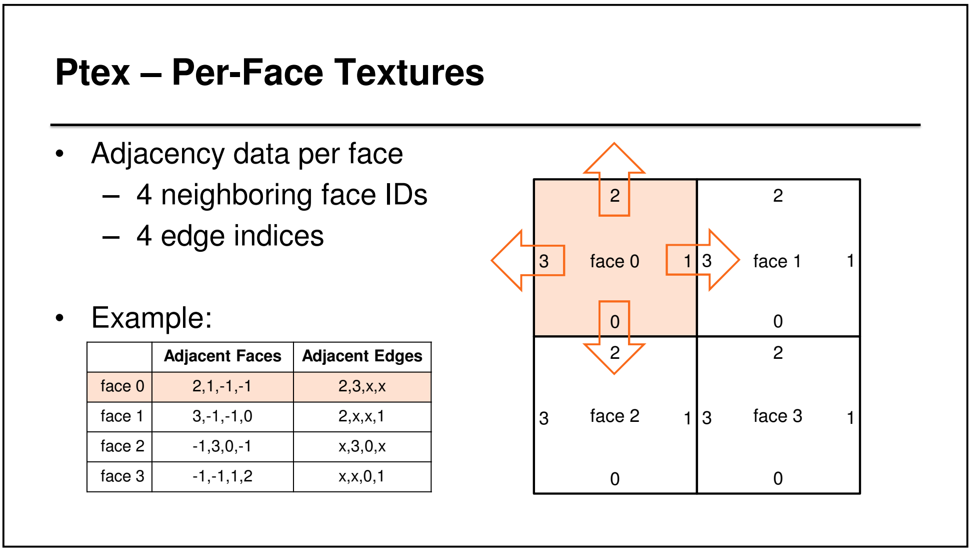
- Separate 2D texture per face
- No need for UV-mapping!
- Filtering near edges requires colors of neighboring faces
- Stores an adjacency list per face

an example quad face

texels

color data locations

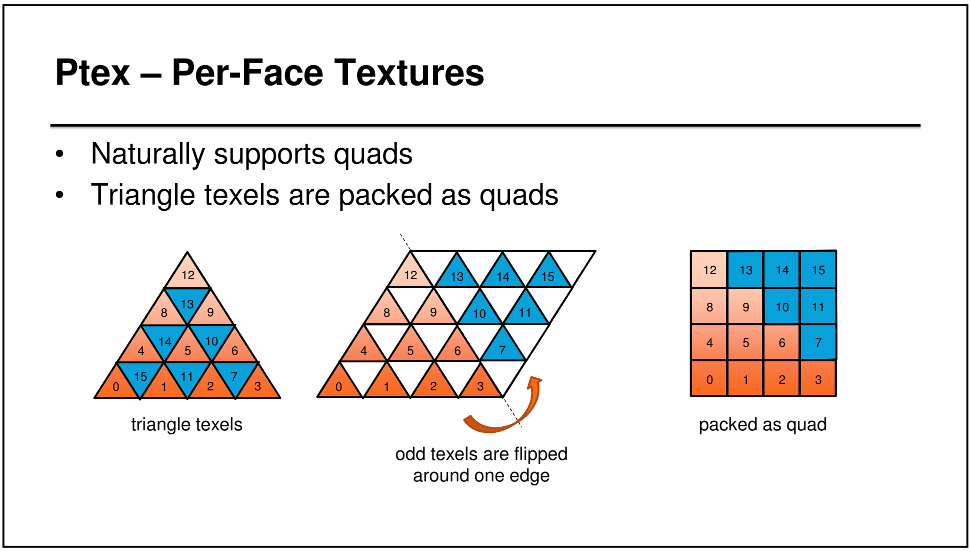
colors of neighboring faces



Ptex – Per-Face Textures

- Adjacency data per face
  - 4 neighboring face IDs
  - 4 edge indices
- Example:

	Adjacent Faces	Adjacent Edges
face 0	2,1,-1,-1	2,3,x,x
face 1	3,-1,-1,0	2,x,x,1
face 2	-1,3,0,-1	x,3,0,x
face 3	-1,-1,1,2	x,x,0,1



Ptex – Per-Face Textures

- Naturally supports quads
- Triangle texels are packed as quads

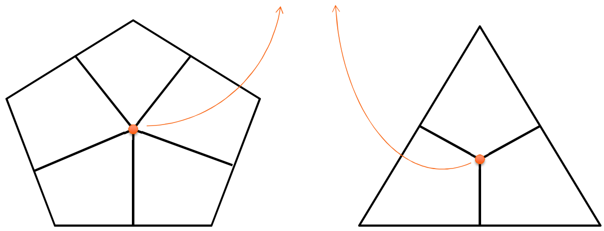
triangle texels

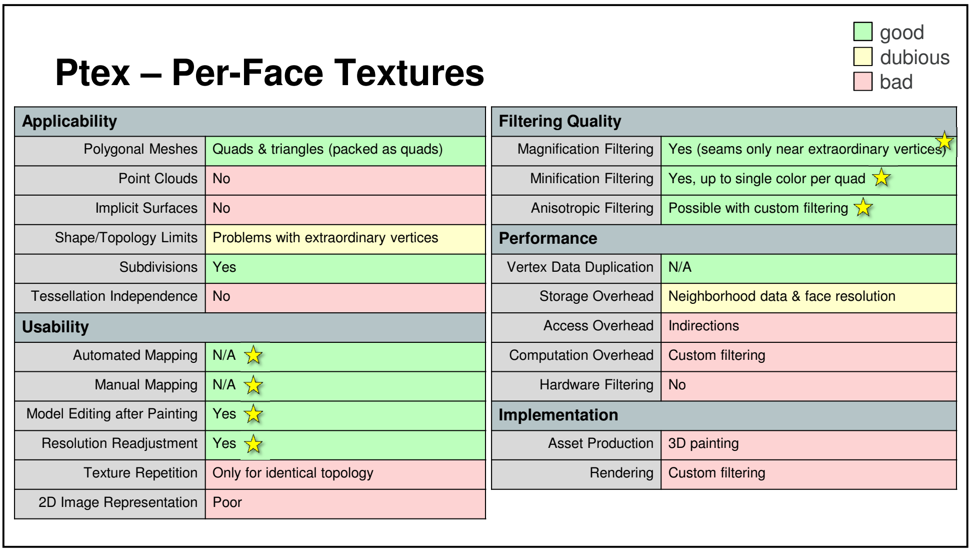
odd texels are flipped around one edge

packed as quad

Ptex – Per-Face Textures

- Custom texture filtering (for filtering across edges)
- Multiple indirect lookups using the adjacency list
- Problems with extraordinary vertices





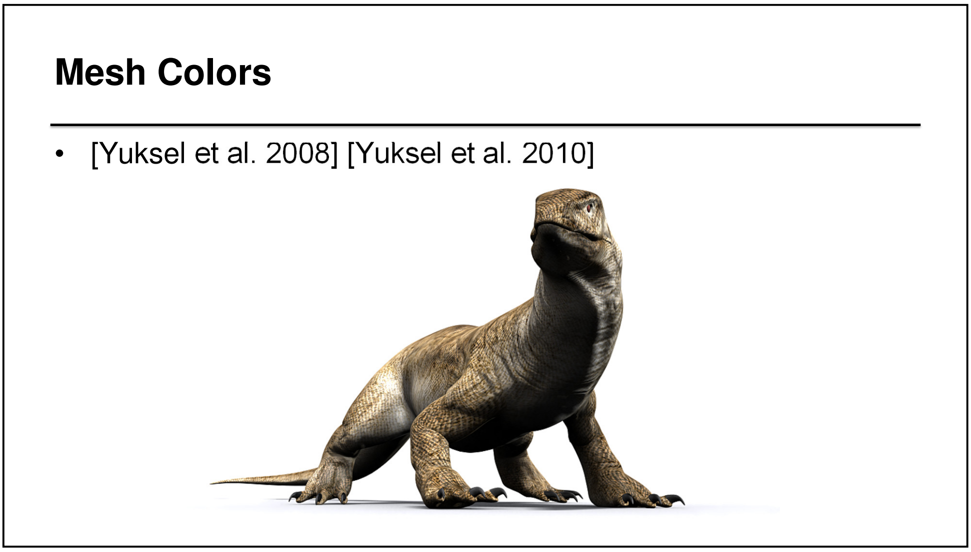
Ptex – Per-Face Textures

🟩 good
🟨 dubious
🟥 bad

Applicability	
Polygonal Meshes	Quads & triangles (packed as quads)
Point Clouds	No
Implicit Surfaces	No
Shape/Topology Limits	Problems with extraordinary vertices
Subdivisions	Yes
Tessellation Independence	No
Usability	
Automated Mapping	N/A ☆
Manual Mapping	N/A ☆
Model Editing after Painting	Yes ☆
Resolution Readjustment	Yes ☆
Texture Repetition	Only for identical topology
2D Image Representation	Poor

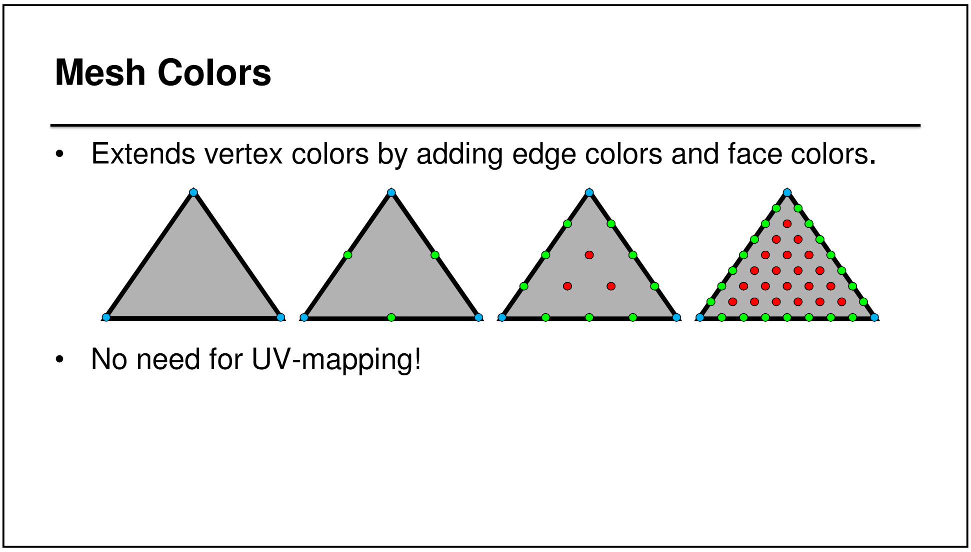
Filtering Quality	
Magnification Filtering	Yes (seams only near extraordinary vertices) ☆
Minification Filtering	Yes, up to single color per quad ☆
Anisotropic Filtering	Possible with custom filtering ☆
Performance	
Vertex Data Duplication	N/A
Storage Overhead	Neighborhood data & face resolution
Access Overhead	Indirections
Computation Overhead	Custom filtering
Hardware Filtering	No
Implementation	
Asset Production	3D painting
Rendering	Custom filtering

5.2 Mesh Colors



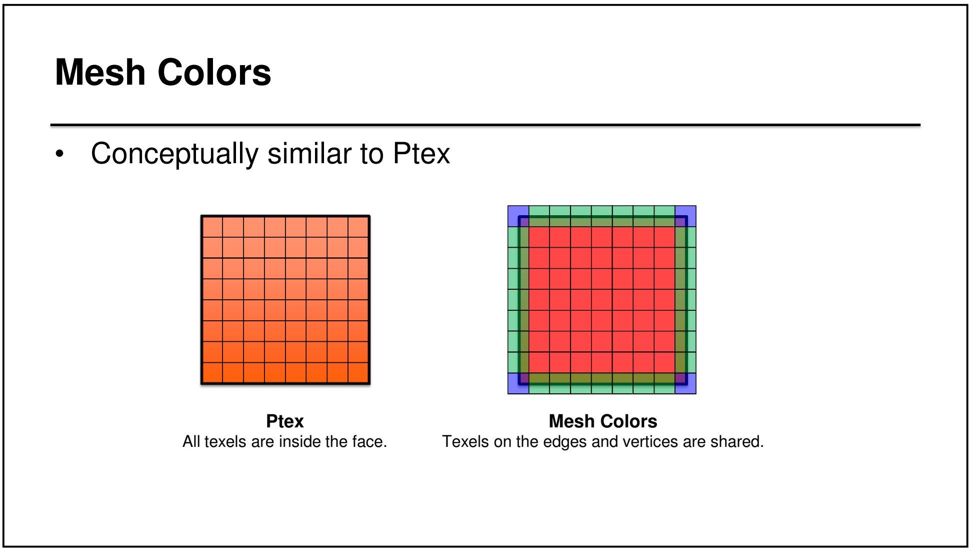
Mesh Colors

- [Yuksel et al. 2008] [Yuksel et al. 2010]



Mesh Colors

- Extends vertex colors by adding edge colors and face colors.
- No need for UV-mapping!

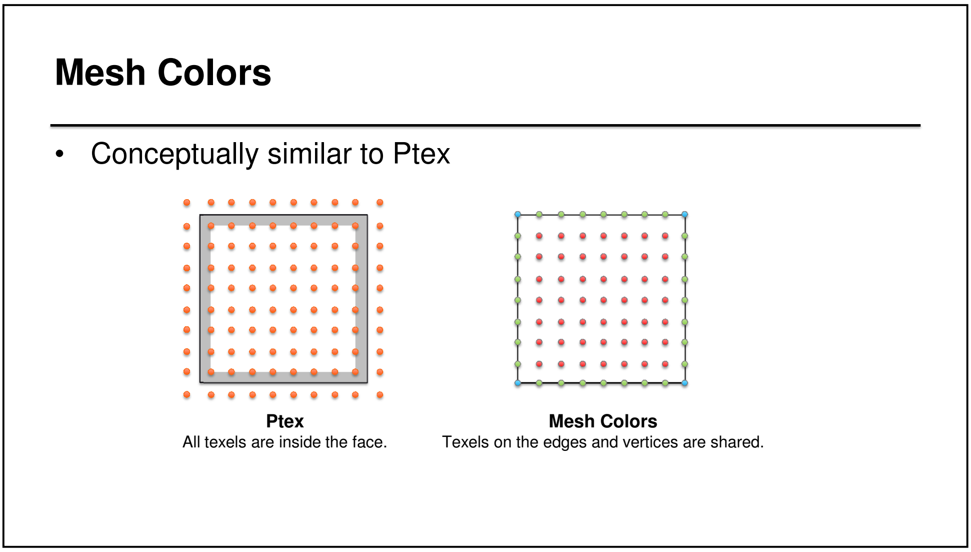


Mesh Colors

- Conceptually similar to Ptex

Ptex
All texels are inside the face.

Mesh Colors
Texels on the edges and vertices are shared.

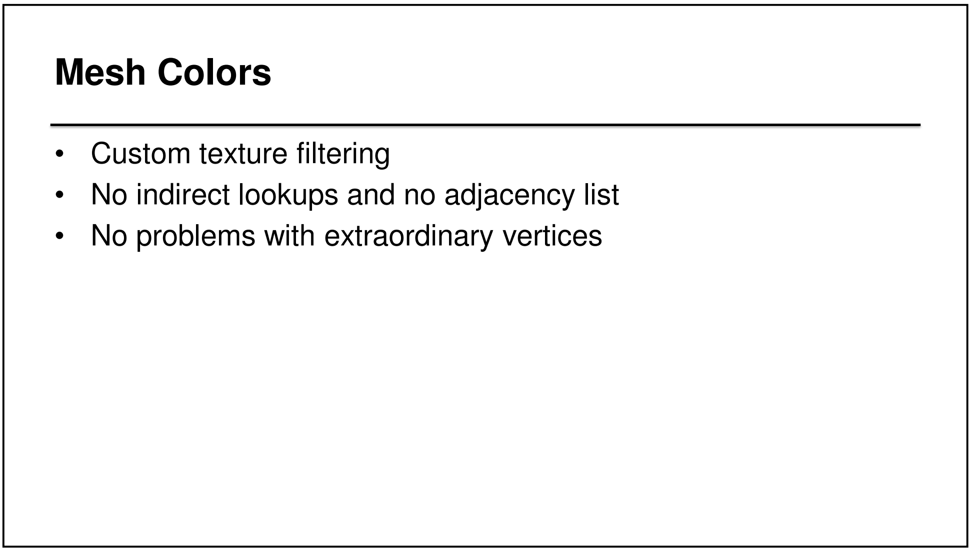


Mesh Colors

- Conceptually similar to Ptex

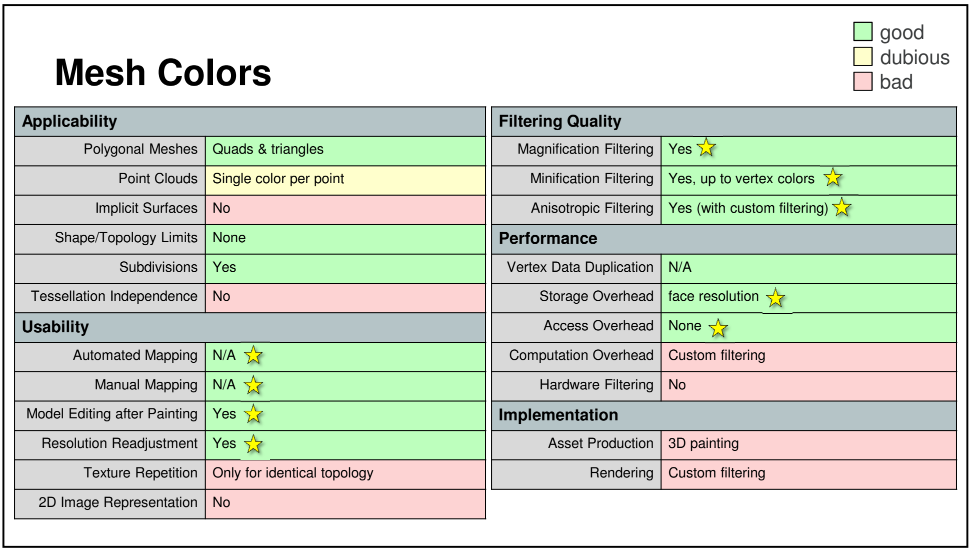
Ptex
All texels are inside the face.

Mesh Colors
Texels on the edges and vertices are shared.



Mesh Colors

- Custom texture filtering
- No indirect lookups and no adjacency list
- No problems with extraordinary vertices



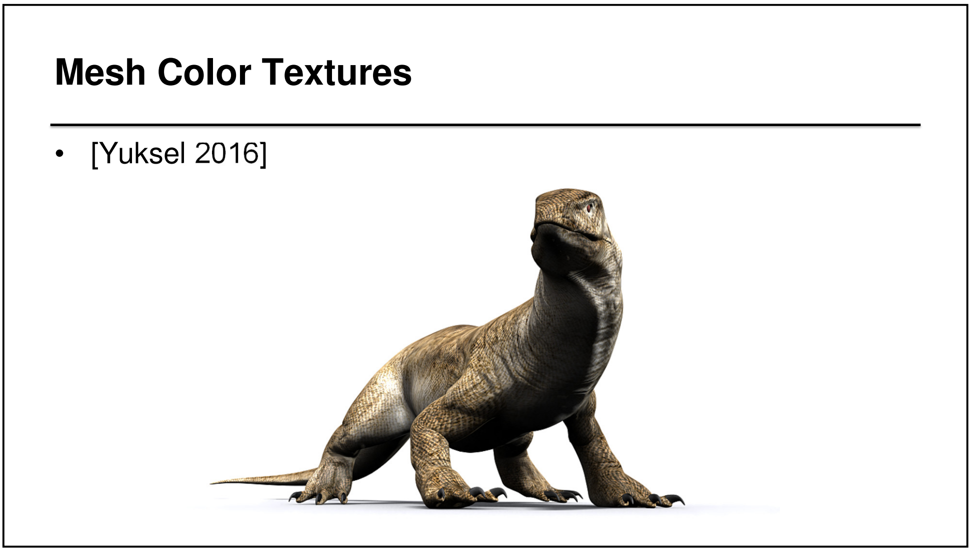
Mesh Colors

🟩 good
🟨 dubious
🟥 bad

Applicability	
Polygonal Meshes	Quads & triangles
Point Clouds	Single color per point
Implicit Surfaces	No
Shape/Topology Limits	None
Subdivisions	Yes
Tessellation Independence	No
Usability	
Automated Mapping	N/A ★
Manual Mapping	N/A ★
Model Editing after Painting	Yes ★
Resolution Readjustment	Yes ★
Texture Repetition	Only for identical topology
2D Image Representation	No

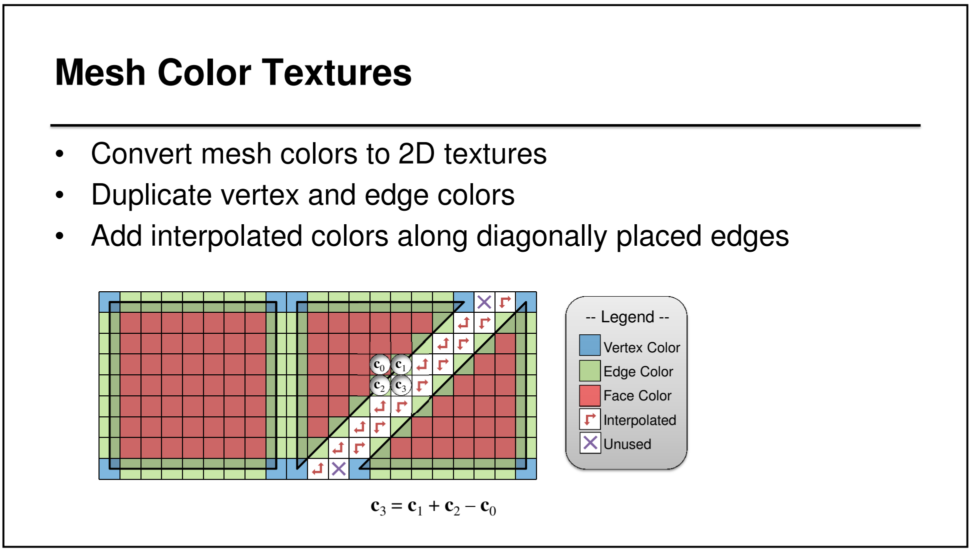
Filtering Quality	
Magnification Filtering	Yes ★
Minification Filtering	Yes, up to vertex colors ★
Anisotropic Filtering	Yes (with custom filtering) ★
Performance	
Vertex Data Duplication	N/A
Storage Overhead	face resolution ★
Access Overhead	None ★
Computation Overhead	Custom filtering
Hardware Filtering	No
Implementation	
Asset Production	3D painting
Rendering	Custom filtering

5.3 Mesh Color Textures



Mesh Color Textures

- [Yuksel 2016]



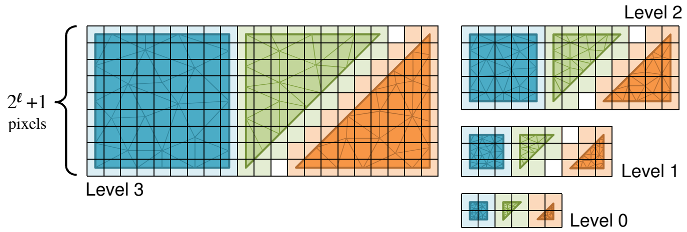
Mesh Color Textures

- Convert mesh colors to 2D textures
- Duplicate vertex and edge colors
- Add interpolated colors along diagonally placed edges

$\mathbf{c}_3 = \mathbf{c}_1 + \mathbf{c}_2 - \mathbf{c}_0$

Mesh Color Textures

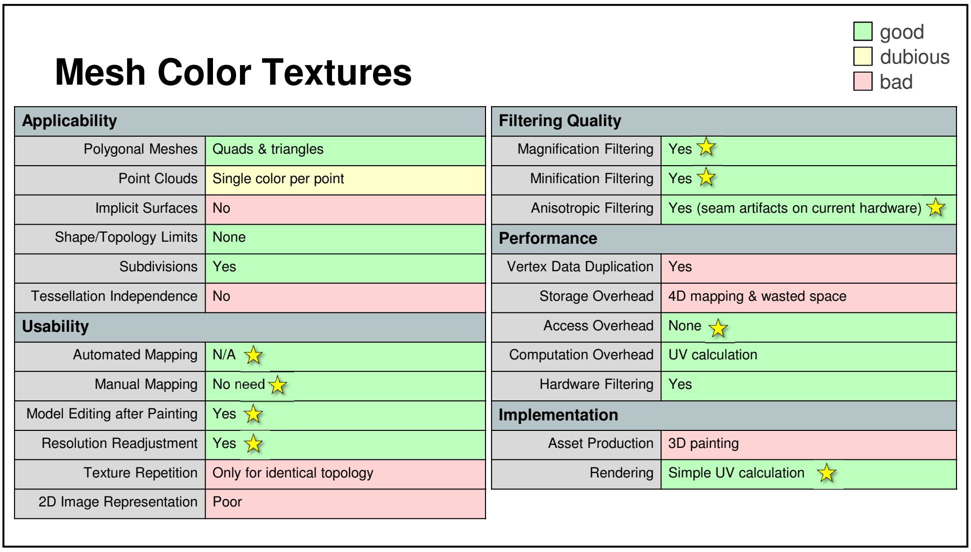
- Mipmap levels (ℓ)



- 4D texture coordinates ($\mathbf{u}_s$, $\mathbf{u}_d$)
  - 2D texture coordinate for level ℓ is $\mathbf{u}_\ell = \mathbf{u}_s / 2^\ell + \mathbf{u}_d$

Mesh Color Textures

- Hardware texture filtering
- Mip-map levels are stored in separate textures
- 2 texture calls for trilinear filtering
- Minimal computation overhead
  - Pick mip-map level
  - Convert 4D texture coordinate to 2D
  - Lerp results



Mesh Color Textures

🟩 good
🟨 dubious
🟥 bad

Applicability	
Polygonal Meshes	🟩 Quads & triangles
Point Clouds	🟨 Single color per point
Implicit Surfaces	🟥 No
Shape/Topology Limits	🟩 None
Subdivisions	🟩 Yes
Tessellation Independence	🟥 No
Usability	
Automated Mapping	🟩 N/A ☆
Manual Mapping	🟩 No need ☆
Model Editing after Painting	🟩 Yes ☆
Resolution Readjustment	🟩 Yes ☆
Texture Repetition	🟥 Only for identical topology
2D Image Representation	🟥 Poor

Filtering Quality	
Magnification Filtering	🟩 Yes ☆
Minification Filtering	🟩 Yes ☆
Anisotropic Filtering	🟩 Yes (seam artifacts on current hardware) ☆
Performance	
Vertex Data Duplication	🟥 Yes
Storage Overhead	🟥 4D mapping & wasted space
Access Overhead	🟩 None ☆
Computation Overhead	🟩 UV calculation
Hardware Filtering	🟩 Yes
Implementation	
Asset Production	🟥 3D painting
Rendering	🟩 Simple UV calculation ☆

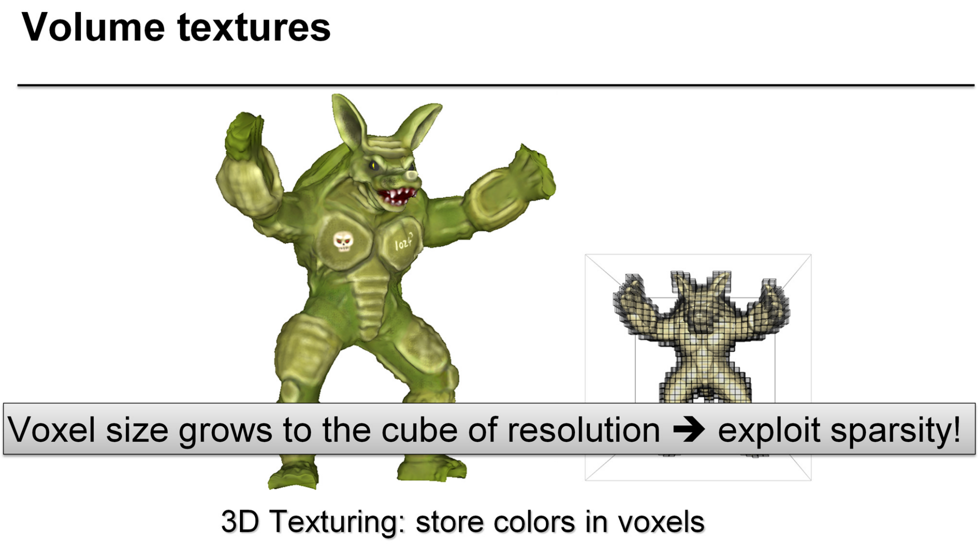
6 SPARSE VOLUMETRIC TEXTURES

30 JULY–3 AUGUST Los Angeles
SIGGRAPH2017

Sparse Volume Textures

RETHINKING TEXTURE MAPPING

We will now discuss a set of methods that share a common idea: defining texture information in a volume surrounding the surface.



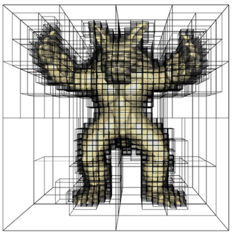
Volume textures

Voxel size grows to the cube of resolution ➔ exploit sparsity!

3D Texturing: store colors in voxels

Here you can see on the left a textured surface, and on the right the set of voxels which encode the colors.
Of course only few voxels are actually useful: those that intersect the surface. Thus storing the full volume would be a bad idea: a vast percentage of memory would be wasted on voxels which are never accessed.

Sparse Volume Methods



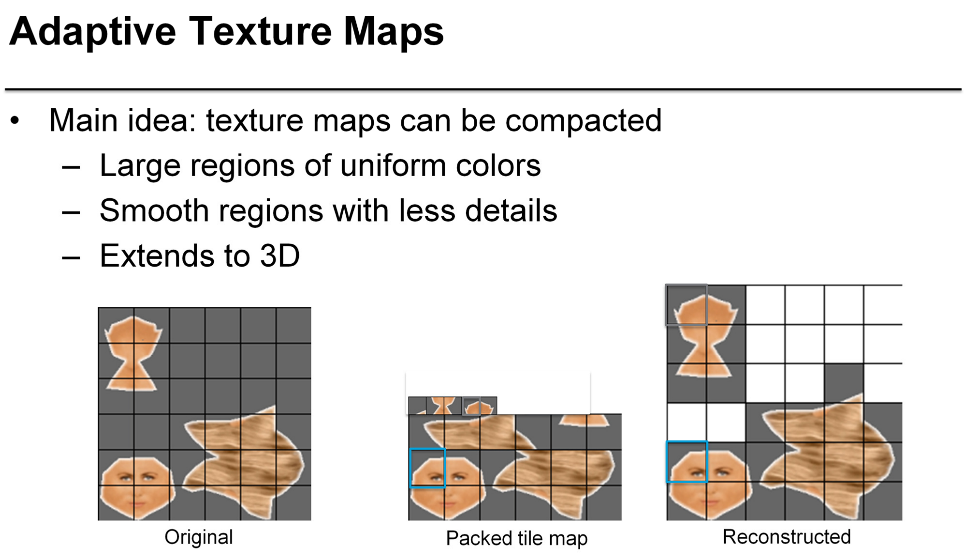
Adaptive texture maps
[Kraus and Ertl 2002]

Octree textures, N^3-Trees, Brickmaps, and Gigavoxels
[Benson and Davis 2002; Christensen and Batali 2004; Lefebvre et al. 2005 ; Lefohn et al. 2006; Crassin et al. 2009]

Spatial Hashing
[Lefebvre and Hoppe 2006, Alcantara et al. 2009-2011, Garcia et al. 2011]

Several schemes have been proposed to encode such sparse textures for computer graphics applications. We will discuss adaptive texture maps, octree textures and its variants, as well as spatial hashing.

6.1 Adaptive Texture Maps



Adaptive Texture Maps

- Main idea: texture maps can be compacted
    - Large regions of uniform colors
    - Smooth regions with less details
    - Extends to 3D

Original

Packed tile map

Reconstructed

One of the first techniques to try to skip over never accessed data are the Adaptive Texture Maps of Kraus and Ertl.
The idea is to introduce an indirection in the texture. The indirection table is a regular grid that covers the texture space. Each cell can be either empty, or it contains the coordinates of a tile. During texture lookup, if the grid cell is empty a background color is returned – but usually these cells are never accessed. If the grid cell is not empty, then the lookup coordinate is transformed into a coordinate in the packed tile map, where the actual texture lookup is performed.

There are several benefits: there is less memory waste, and it is also possible to scale up or down each individual tile, for instance lowering the resolution in regions having smooth color variations. It is even possible to do instancing, by reusing a tile in several entries of the indirection map.

Of course this idea extends to 3D as well.

🟩 good
🟨 dubious
🟥 bad

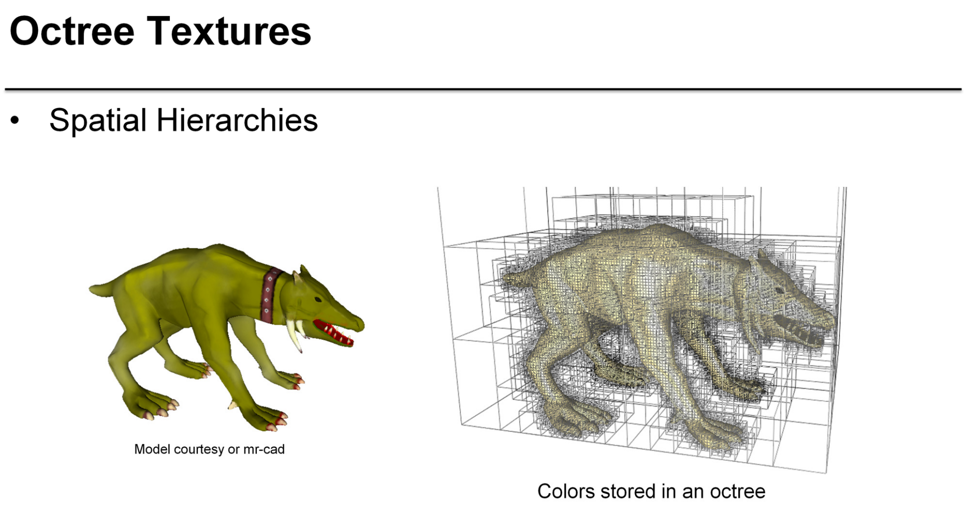
Adaptive texture maps

Applicability	
Polygonal Meshes	🟩 Yes
Point Clouds	🟥 No
Implicit Surfaces	🟥 No
Shape/Topology Limits	🟩 None
Subdivisions	🟩 Yes
Tessellation Independence	🟥 If seams are preserved
Usability	
Automated Mapping	🟥 Limited
Manual Mapping	🟥 Often needed
Model Editing after Painting	🟥 Problematic
Resolution Readjustment	🟩 Yes (local increase in image space)
Texture Repetition	🟩 Yes (+ instancing)
2D Image Representation	🟥 Poor

Filtering Quality	
Magnification Filtering	🟩 Yes
Minification Filtering	🟨 Yes (up to tile size)
Anisotropic Filtering	🟥 Yes, with seam artifacts
Performance	
Vertex Data Duplication	🟥 Yes
Storage Overhead	🟨 2D mapping (uv) + indirection map
Access Overhead	🟨 Single indirection
Computation Overhead	🟨 Indirection, tile map construction
Hardware Filtering	🟩 Yes
Implementation	
Asset Production	🟩 Standard UVs + automated tile construction
Rendering	🟩 Single indirection

Adaptive texture maps are a simple but efficient way to skip empty space in textures, and provides additional flexibility such as local resolution adjustment. However, even though they require a single indirection, this requires a custom shader to correctly perform interpolation and MIP-mapping.
Also, in volumes, the single indirection does not allow a tight fit around the surface, meaning that a lot of empty space is still stored.

6.2 Octree Textures, Brickmaps, N^3 Trees, and Gigavoxels



Octree Textures

- Spatial Hierarchies

Model courtesy or mr-cad

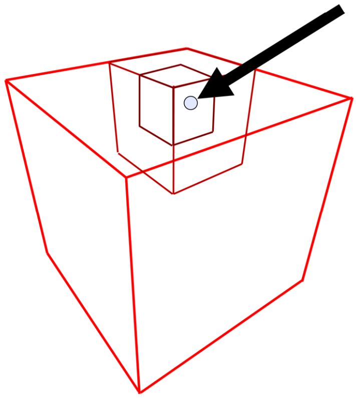
Colors stored in an octree

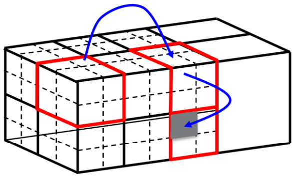
Octree texture focus exactly on this issue, by generalizing to multiple lookups. Here you can see on the lest a colored 3D model, and on the right the octree that encodes the color content. You can see how the structure densify around the surface until it reaches the desired voxel resolution.

Colors are stored in the octree leaves, but also in internal nodes for MIP-mapping.

Octree Textures

- Lookup from surface point





Node pool (3D, 8bit RGBA)

[Octree Textures on the GPU, GPU Gems 2, 2005]

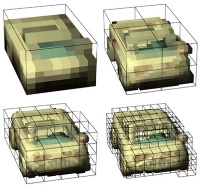
(animation)
Here is how the lookup is performed. The root node is in red, and the lookup point is the white circle. The coordinates of the lookup point are first expressed as coordinates within the root node. On the right, you can see the 3D texture that stores the actual tree nodes, which we call the node pool.

Each node is a small 2x2x2 brick, that stores coordinates to its child nodes within the node pool, or colors. Having the coordinate of the lookup point within the root, we read the coordinates of its child node.
We then compute the coordinates of the lookup point within the child done, and access it in the node pool. This gives us a new child node coordinate, that we access similarly. This time a color is retrieved: we reached the bottom of the octree.

This is a very simple process to implement. The main drawback is that it requires several dependent lookups, log(N) of them with N the texture resolution.

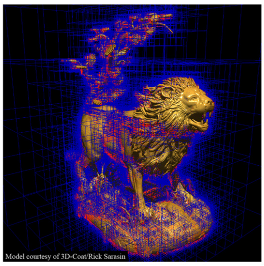
Generalizations

- Brickmaps, N^3 trees
    - Split by more than 2 at each level
    - Memory-access tradeoff
    - Optimized for off-line rendering (cache)



[Christensen and Batali 2004]

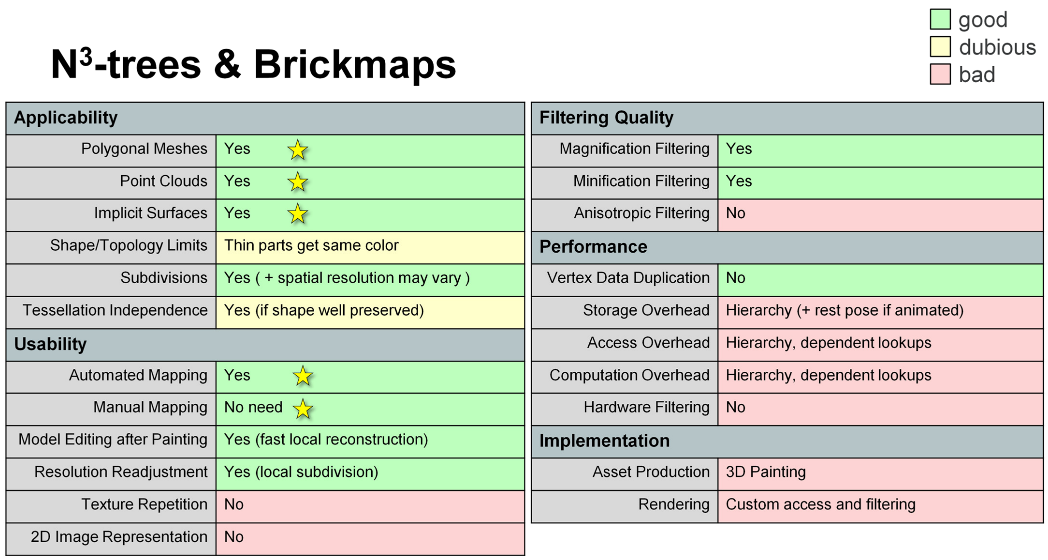
- Gigavoxels
    - Stores opacity for volume rendering
    - Produces / loads content during traversal



Model courtesy of 3D-Coat/Rick Sarasin

This idea has been generalized to subdivide the node into more than 2x2x2. This allows a tradeoff between memory and access depth. Indeed the octree provides the tighter fit, but reaching the bottom of a 4096 cube tree require 12 lookups. Instead, using 8x8x8 subdivisions will require only 4 lookups – but will use more memory.

Another extension of this idea is to store density in space for volume rendering. This has been done by Gigavoxel, which also introduces an efficient stackless traversal and proposes to generate volume data on-the-fly, only when needed for rendering.



N^3-trees & Brickmaps

🟩 good
🟨 dubious
🟥 bad

Applicability	
Polygonal Meshes	Yes ☆
Point Clouds	Yes ☆
Implicit Surfaces	Yes ☆
Shape/Topology Limits	Thin parts get same color
Subdivisions	Yes (+ spatial resolution may vary)
Tessellation Independence	Yes (if shape well preserved)
Usability	
Automated Mapping	Yes ☆
Manual Mapping	No need ☆
Model Editing after Painting	Yes (fast local reconstruction)
Resolution Readjustment	Yes (local subdivision)
Texture Repetition	No
2D Image Representation	No

Filtering Quality	
Magnification Filtering	Yes
Minification Filtering	Yes
Anisotropic Filtering	No
Performance	
Vertex Data Duplication	No
Storage Overhead	Hierarchy (+ rest pose if animated)
Access Overhead	Hierarchy, dependent lookups
Computation Overhead	Hierarchy, dependent lookups
Hardware Filtering	No
Implementation	
Asset Production	3D Painting
Rendering	Custom access and filtering

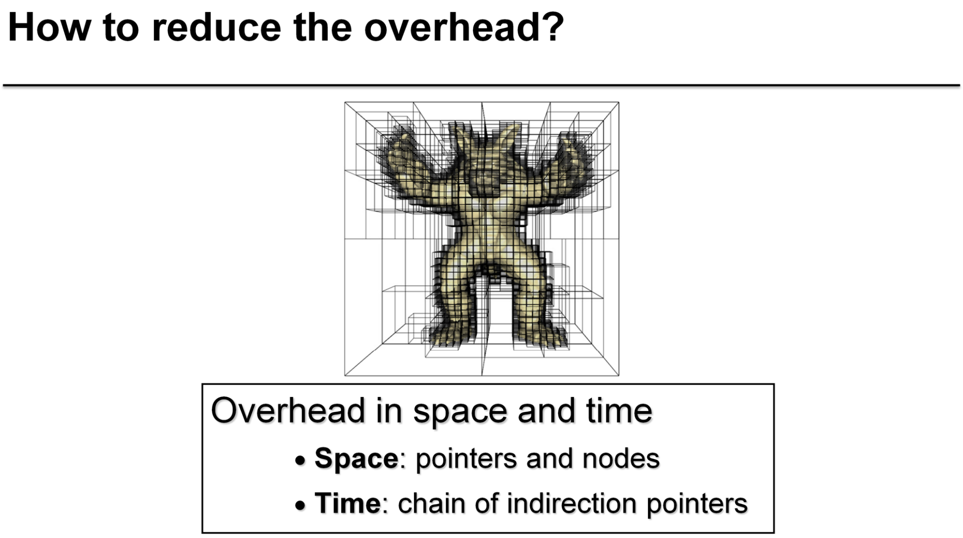
To recap, octrees and their generalizations have the following advantages:
- They require no uv and are very simple to build – nowadays this an be done directly on the GPU
- They afford for simple local resolution adjustment: just subdivide more locally!

However they have one major drawback, which is that they require a rather expensive access with multiple dependent texture lookups. Note that this will run at hundreds of frame per seconds on a modern GPU, but that remains significantly more expensive that regular texture mapping. Another issue is that filtering, in particular interpolation, requires more accesses, as the shader as to implement it with up to eight lookups.

Volume approaches also suffer from a thin sheet limitation: it is not possible to give different colors to surfaces in close proximity ; even though some works suggest using the normal to distinguish between different directional colors.

Finally, like all volume techniques, this requires authoring to be done with a 3D texture painting tool.

6.3 Perfect Spatial Hashing



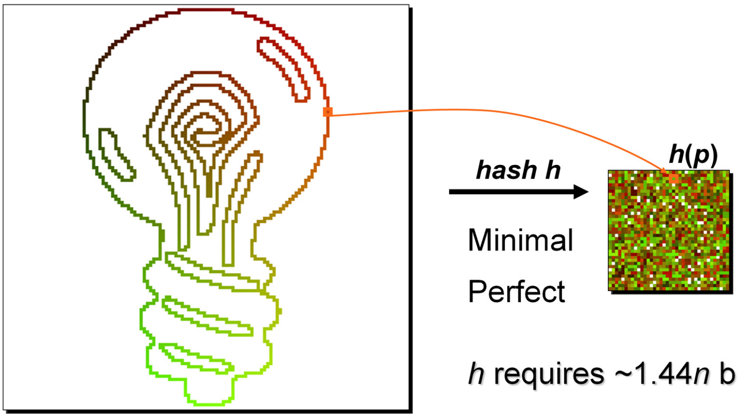
How to reduce the overhead?

Overhead in space and time

- **Space**: pointers and nodes
- **Time**: chain of indirection pointers

The main issues with the octree textures we have seen before is that they are hierarchies: Storing the structure of the hierarchy requires additional memory, and accessing it requires extra time.

Minimal Perfect Hash (2D)



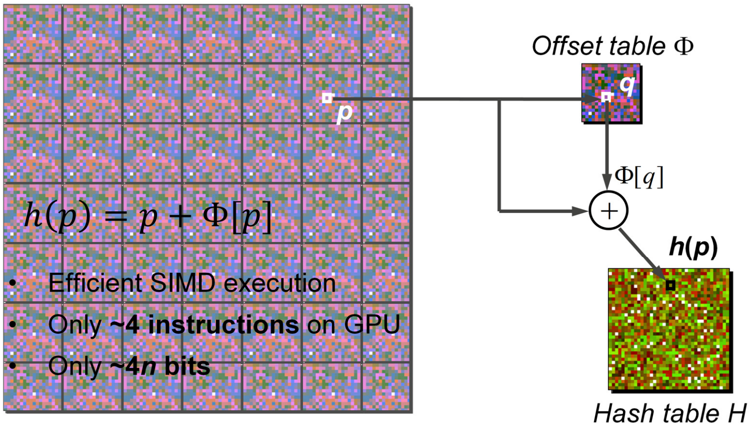
h requires ~1.44*n* bits

Instead, spatial hashing stores only the used pixels (or voxels) in a compact hash table.
The location of a pixel within the table is given by a hash function applied to its coordinates.

In addition it is possible to find minimal perfect hashes. A minimal hash is one where the hash table is full. In other words there are no unused slots.

One important point is that the hash function itself needs to be encoded and this may take up a significant amount of memory. So a key question is how this does compare to the pointers of a hierarchy. Well it turns out that the overhead can be much smaller, as small as 1.44 bits per entry.

Minimal Perfect Hash



$$h(p) = p + \Phi[p]$$

- Efficient SIMD execution
- Only **~4 instructions** on GPU
- Only **~4*n* bits**

The idea of a perfect spatial hash is to encode the hash function using a small auxiliary table, called the offset table. This is inspired by previous work for hashing dictionaries of strings.

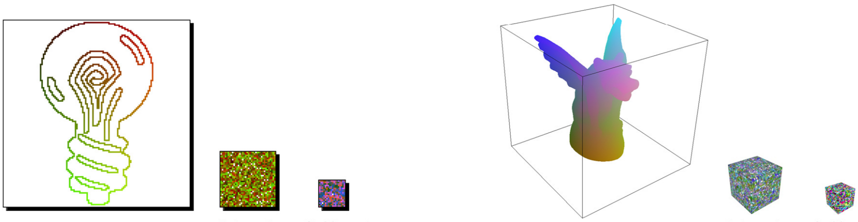
The hash function can be very simple. It starts by accessing the offset table. The access is done using warp around adressing, so many pixels will be mapped to the same location.

The retrieved offset is then added the coordinates of the pixel, and the offset address is used to access the hash table again with modulo addressing.

The challenge of course is to create an offset table so that the resulting hash function is perfect.

As it turns out, it is possible to create a simple hash function that is well suited for GPU evaluation. It contains no branch instructions and enables efficient SIMD execution. It requires only four instructions in most cases, and, on average, only 4 bits per entry. This is more than the theoretical lower bound of 1.44 bits but is still a much smaller overhead than with hierarchies.

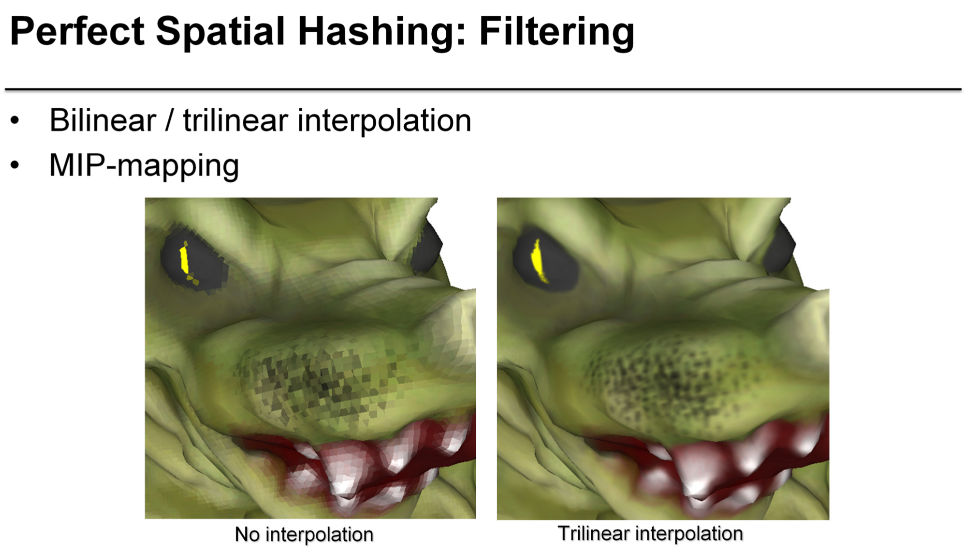
Generalization to 3D



2D sparse → *Hash table* *Offset table*

3D sparse → *Hash table* *Offset table*

This process I just described in 2D is easily extended to 3D. Runtime access has the exact same cost as GPUs perform vector arithmetic.



Perfect Spatial Hashing: Filtering

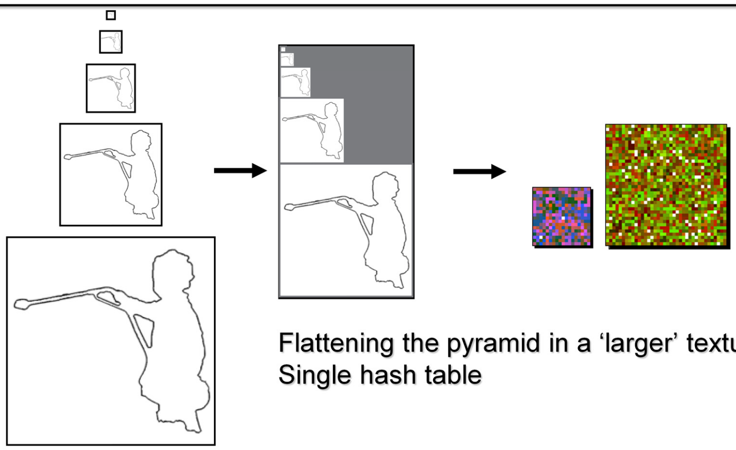
- Bilinear / trilinear interpolation
- MIP-mapping

No interpolation

Trilinear interpolation

Filtering can also get tricky, and the most efficient approach is to encode blocks of texture data as opposed to single values. This results in higher memory usage however.

Perfect Spatial Hashing: MIP-mapping

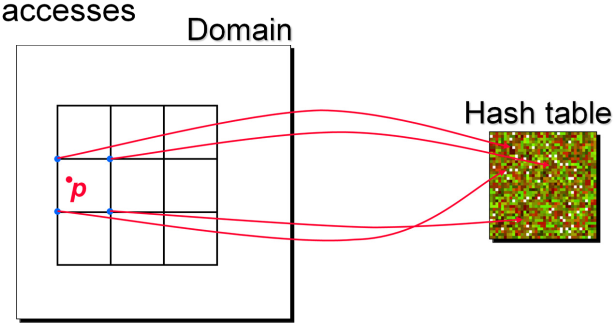


Flattening the pyramid in a ‘larger’ texture
Single hash table

MIP-mapping is supported by flattening the pyramid in a single sparse texture, using the level identifier to compute the new coordinates.

Perfect Spatial Hashing: Interpolation

- Multiple accesses

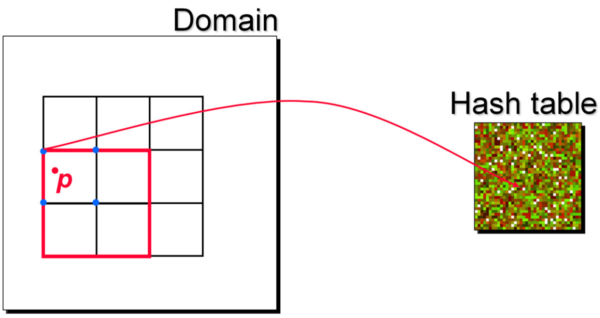


- In 3D, slower by a factor of 3 to 7

Interpolation can be done in the shader with multiple accesses. This is a bit unfortunate, because now we have up to 16 accesses in 3D (eight times the two required for nearest mode access)

Perfect Spatial Hashing: Interpolation

- Blocking



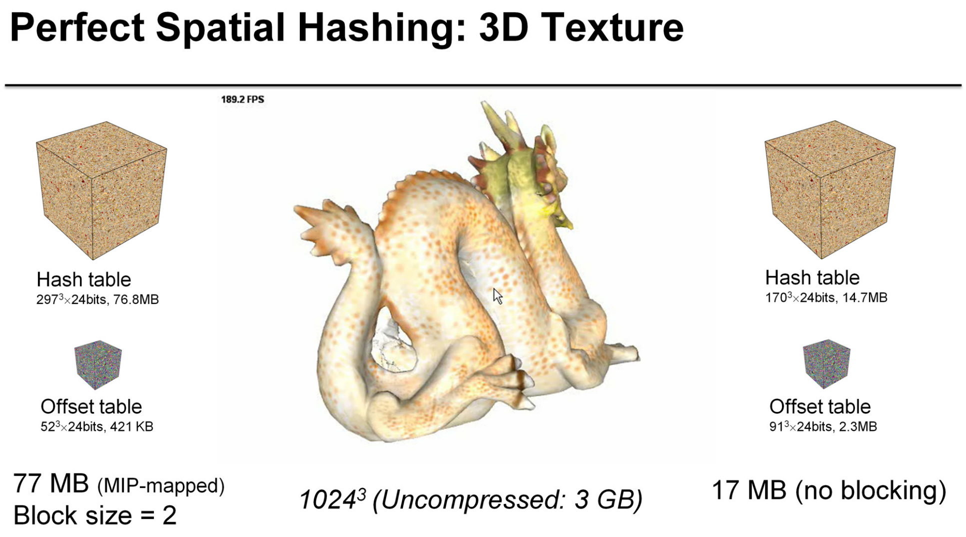
Single hash evaluation

Native bilinear interpolation

But, large memory overhead (x3 with 2x2x2 blocks)

Instead, one possible approach is to use blocking. The idea is to store into the hash small texture blocks, instead of single colors. The boundary color is duplicated between neighboring blocks. The advantage is that native trilinear interpolation can be used, and we are back to two lookups. However, this incurs a large memory overhead.

Btw, this approach can also be used with octrees.



Perfect Spatial Hashing: 3D Texture

Hash table
$297^3 \times 24$bits, 76.8MB

Offset table
$52^3 \times 24$bits, 421 KB

77 MB (MIP-mapped)
Block size = 2

1024^3 (Uncompressed: 3 GB)

Hash table
$170^3 \times 24$bits, 14.7MB

Offset table
$91^3 \times 24$bits, 2.3MB

17 MB (no blocking)

Here you can see a result. In this example the dragon is textured with a sparse 1k cubed volume.
Using a blocked hash for native trilinear interpolation, the texture fits in 77 MB, including MIP-mapping – this is shown on the left. On the right, without the blocking the storage is down to 17MB.

🟩 good
🟨 dubious
🟥 bad

Perfect Spatial Hashing

Applicability	
Polygonal Meshes	🟩 Yes
Point Clouds	🟩 Yes ☆
Implicit Surfaces	🟩 Yes ☆
Shape/Topology Limits	🟨 Thin parts get same color
Subdivisions	🟩 Yes (spatial resolution may vary)
Tessellation Independence	🟨 Yes (if shape well preserved)
Usability	
Automated Mapping	🟩 Yes, but slow
Manual Mapping	🟩 No need
Model Editing after Painting	🟥 No
Resolution Readjustment	🟥 No
Texture Repetition	🟥 No
2D Image Representation	🟥 No

Filtering Quality	
Magnification Filtering	🟩 Yes
Minification Filtering	🟩 Yes
Anisotropic Filtering	🟥 No
Performance	
Vertex Data Duplication	🟩 No
Storage Overhead	🟥 With blocking: ~ 4bits per entry + borders
	🟨 Without blocking: ~ 4bits per entry ☆
Access Overhead	🟨 Single indirection ☆
Computation Overhead	🟥 Hash pre-computation, indirection
Hardware Filtering	🟥 No
Implementation	
Asset Production	🟥 3D Painting
Rendering	🟩 With blocking: single indirection
	🟥 Without blocking: custom shader

Perfect spatial hashing solves one of the key issues of hierarchies, the multiple dependent accesses, while preserving a tight storage.
It requires only one indirection for nearest mode lookups, but unfortunately things become less elegant with interpolation, which either incurs an access overhead, or a memory overhead.
The construction process of perfect spatial hashing is easy to implement, however it can take a long time as it is based on a stochastic exploration.

7 VOLUME-BASED PARAMETERIZATIONS

30 JULY–3 AUGUST Los Angeles
SIGGRAPH2017

Volume-based Parameterizations

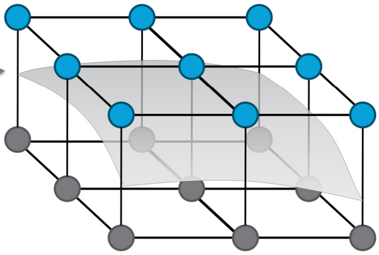
RETHINKING TEXTURE MAPPING

We will now discuss a set of methods that share a common idea: defining texture information in a volume surrounding the surface.

7.1 TileTrees

TileTrees: Motivation

- Volume textures are great but:
  - Interpolation requires 8 lookups
  - Interpolation requires 8 samples

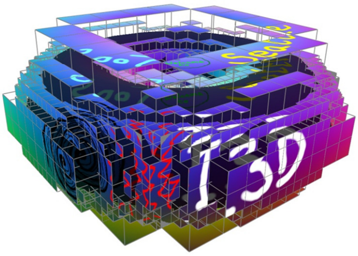


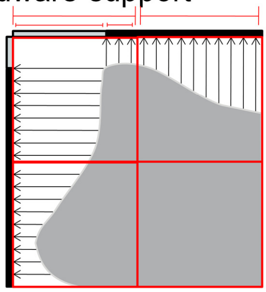
Could use only top ***or*** *bottom samples*

The main motivation of the tiletree is that, when texturing a surface with a volume, some additional samples are stored. For instance, in this figure, the piece of surface is near horizontal, and clearly only the top (pink) samples would be enough to define a color field – of course the bottom ones would be fine as well, but the point is that we do not need both.

TileTrees: Key Idea

- Position 2D square tiles around the surface
- Project onto tiles at rendering time
  - Volume for positioning: simplicity + versatility
  - 2D square tiles: efficiency + hardware support

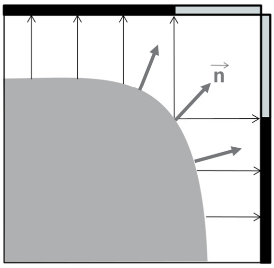




(animated)
So what the tile tree does is to use a volume hierarchy – a shallow octree – to position 2D tiles around the surface. Then the tiles are looked up from the surface, by a simple projection.
This is illustrated on the right, for a side view. The arrows are showing how the surface projects onto the tiles.
Here you can see for volume cells, and this red interval is a 2D tile, and this is another, and here you can see which part is actually used, while this other is not.

TileTrees: Implicit Parameterization

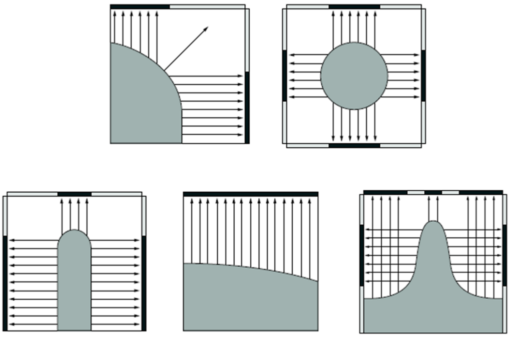
- Within each tree leaf:
  - Surface projected onto tiles
  - Implicit local parameterization using normal



Now, instead of storing an actual mapping, the idea is simply use the normal – so obviously this requires normal to be defined along the surface. The mapping is thus implicit, and the projection is performed along the axis that is most aligned with the normal. This can be +/- X, +/-Y or +/- Z.
During construction, the algorithm ensures that all required tiles are there.

TileTrees: Implicit Parameterization

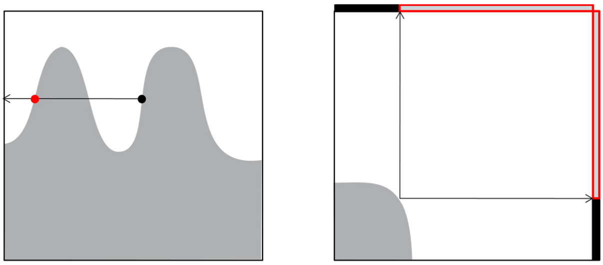
Quite powerful:



This approach is surprisingly powerful, here you can see a number of configurations that are supported.

TileTrees: Implicit Parameterization

When does it break?



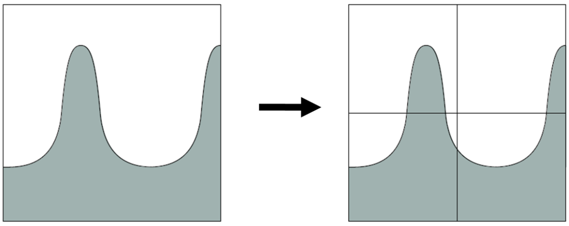
Incorrect ! Low coverage !

- What if it *does* break?

However it does break in some cases, such as this double bump. So what happens in such a case?

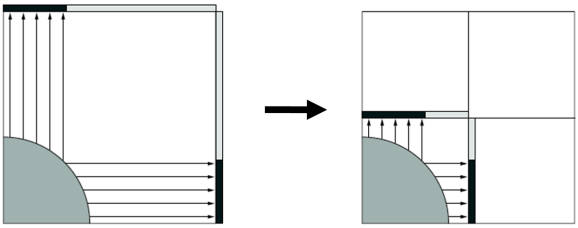
TileTrees: Subdividing

If incorrect ➔ subdivide



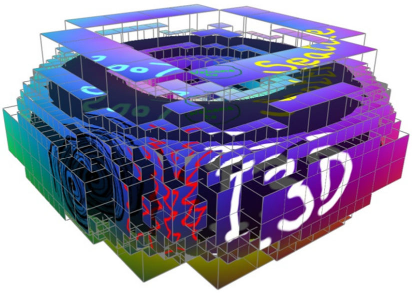
This is why there is a hierarchy. In such a case the cell is subdivided to allow for additional, smaller tiles to be positioned.

TileTrees: Subdividing

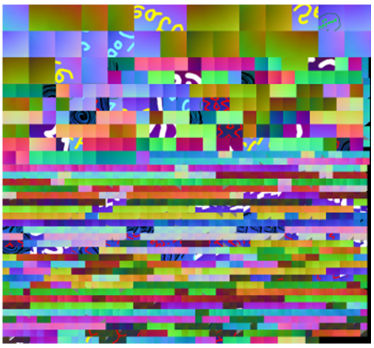


Another case for subdivision is when the tile is not well covered: this would be wasteful.

TileTrees: Storage



Shallow hierarchy



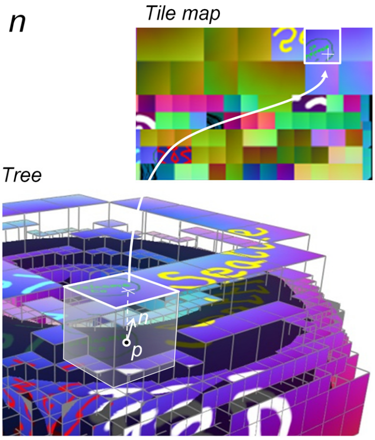
Tile map

So, here is the result for a torus. On the left a visualization of the tiletree in space ; on the right the texture storing all the tiles.

TileTrees: Lookup

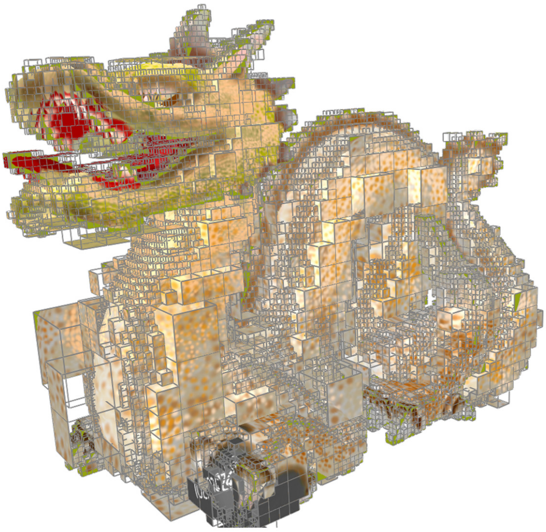
For a surface point *p* with normal *n*

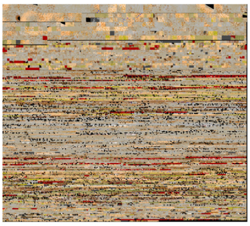
1. Lookup the tree at *p*
2. Select leaf-face with *n*
3. Project *p* onto face
4. Access tile map



The lookup process is fairly simple: first locate the cell enclosing the point, then select a face using the normal, project the point onto it and finally access the tile map using standard texture accesses. It gets more involved to properly define filtering across tile boundaries, but that can be done. The final shader is about 30 lines, with 10 texture lookups when the hierarchy has three levels.

Dragon 1024^3 RGB
11.3 MB *depth = 7, 26458 tiles*





Here is a more complex result, and the same dragon as before.

As you can see, this uses 11.3 MB versus 17 MB for the perfect hash *without blocking*. This means that in this case it provides a more compact representation with less overhead for the filtered access.

🟩 good
🟨 dubious
🟥 bad

TileTrees

Applicability	
Polygonal Meshes	🟩 Yes ★
Point Clouds	🟨 Yes (if normal available)
Implicit Surfaces	🟩 Yes ★
Shape/Topology Limits	🟨 Limited local complexity
Subdivisions	🟩 Yes
Tessellation Independence	🟨 Yes (if shape well preserved)
Usability	
Automated Mapping	🟩 Yes
Manual Mapping	🟩 No need
Model Editing after Painting	🟥 No
Resolution Readjustment	🟩 Yes (increase tile resolution)
Texture Repetition	🟥 No
2D Image Representation	🟥 Poor

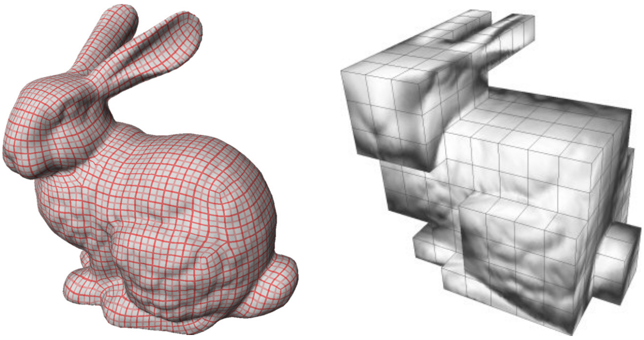
Filtering Quality	
Magnification Filtering	🟩 Yes
Minification Filtering	🟩 Yes (up to tile size)
Anisotropic Filtering	🟥 No (tile boundaries)
Performance	
Vertex Data Duplication	🟩 No
Storage Overhead	🟨 Shallow tree hierarchy then 2D tiles (+ rest pose if animated) ★
Access Overhead	🟥 Few indirections, relies on 2D textures
Computation Overhead	🟥 Indirections
Hardware Filtering	🟥 No
Implementation	
Asset Production	🟥 3D Paintings
Rendering	🟥 Custom access and filtering

To recap, the tiletree is another technique that requires no UV. The lookup is fairly simple, and builds upon 2D filtering in the tilemap, but requires several accesses. One drawback is that the construction process is more difficult to implement than an octree or a hash map. It computes faster than a hash but still slower than an octree. The access overhead, even if smaller especially with interpolation, remains much more expensive than a standard texture map. Also keep in mind the comparison is subtle because there is a memory-access tradeoff.

7.2 PolyCube Maps

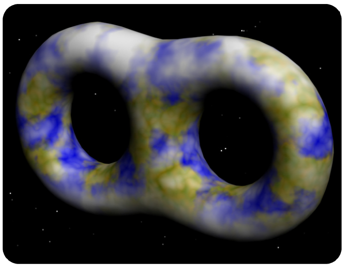
Polycube-Maps

- [Tarini et-al 2014]



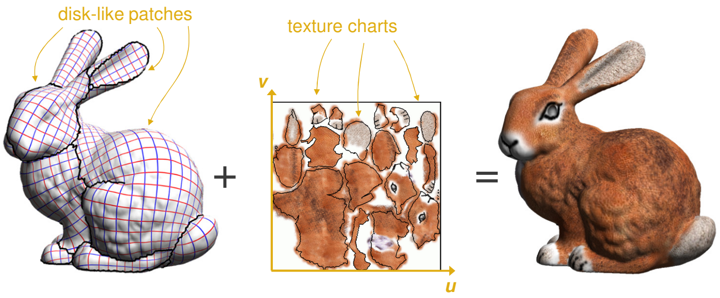
The Goal

- Texture mapping
  - – seamless
  - – hardware supported
  - – low distortion
  - – general object



Texture Atlas

(multi-chart approach to parameterization)



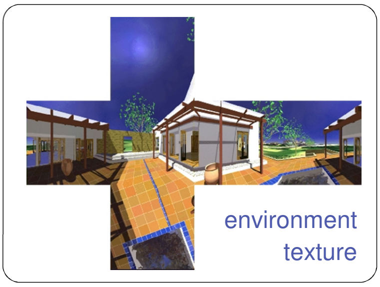
3D mesh 2D texture image textured bunny

images courtesy of ***Lévy***, ***Sylvain***, ***Ray*** *and* ***Maillot*** *, SIGGRAPH 02*

Cube-Maps

- Typically used for *environment mapping*

mesh

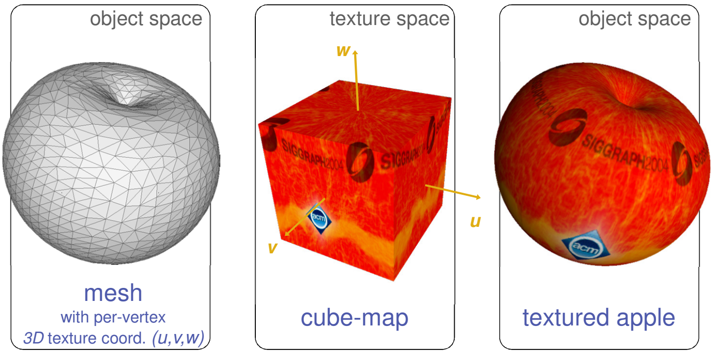


environment texture

images from Bubble demonstration program, ***nVidia***

Abusing Cube-Maps

- What if we store surface color in a cube-map?



Abusing Cube-Maps

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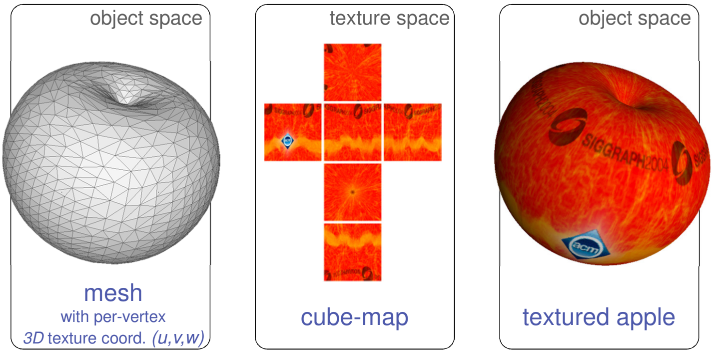
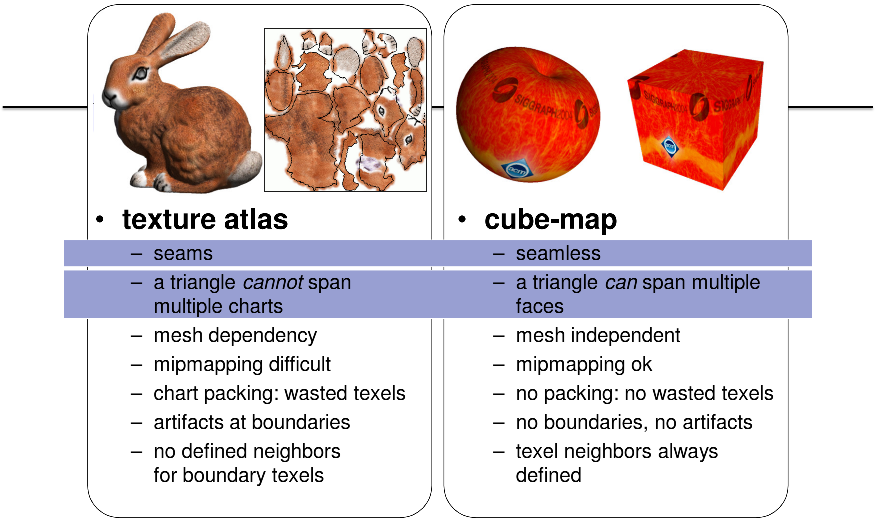
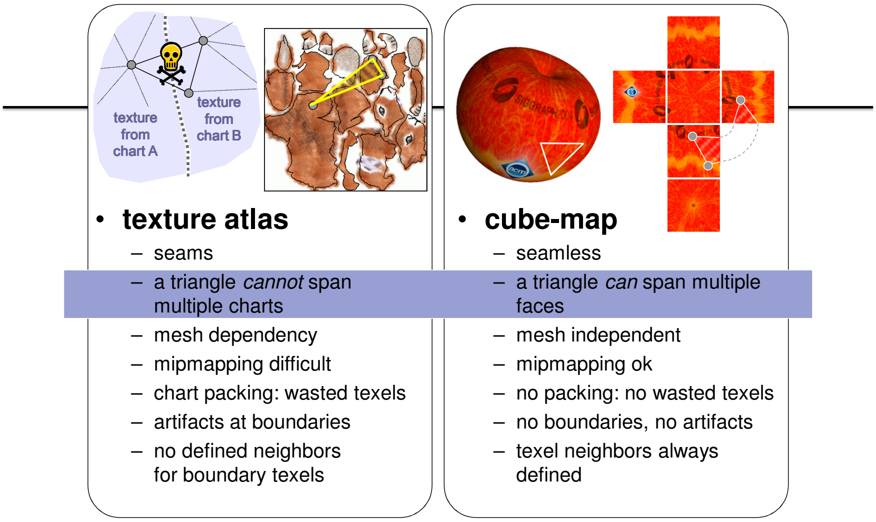




- **texture atlas**
  - seams
  - a triangle *cannot* span multiple charts
  - mesh dependency
  - mipmapping difficult
  - chart packing: wasted texels
  - artifacts at boundaries
  - no defined neighbors for boundary texels

- **cube-map**
  - seamless
  - a triangle *can* span multiple faces
  - mesh independent
  - mipmapping ok
  - no packing: no wasted texels
  - no boundaries, no artifacts
  - texel neighbors always defined



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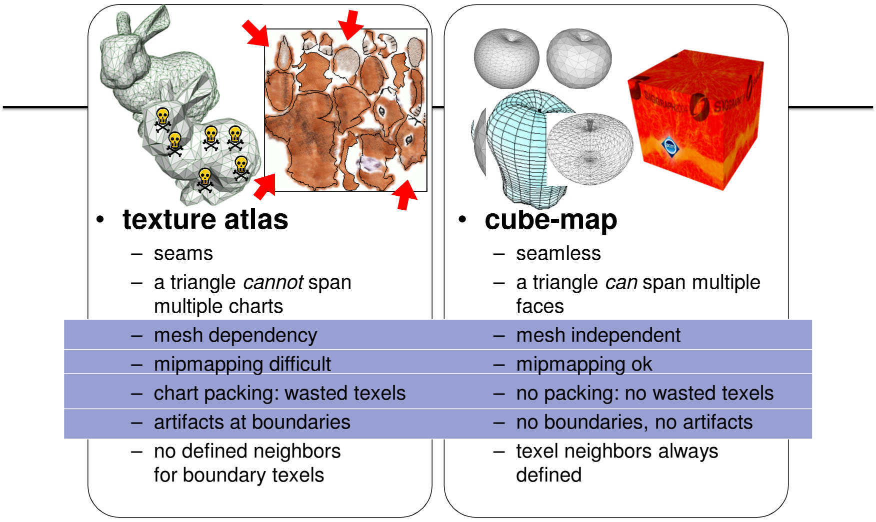

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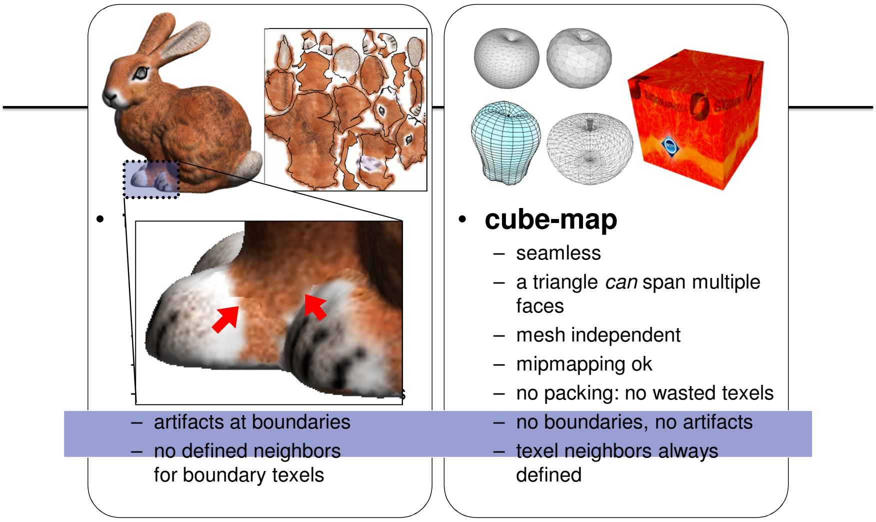

-
  - artifacts at boundaries
  - no defined neighbors for boundary texels

- **cube-map**
  - seamless
  - a triangle *can* span multiple faces
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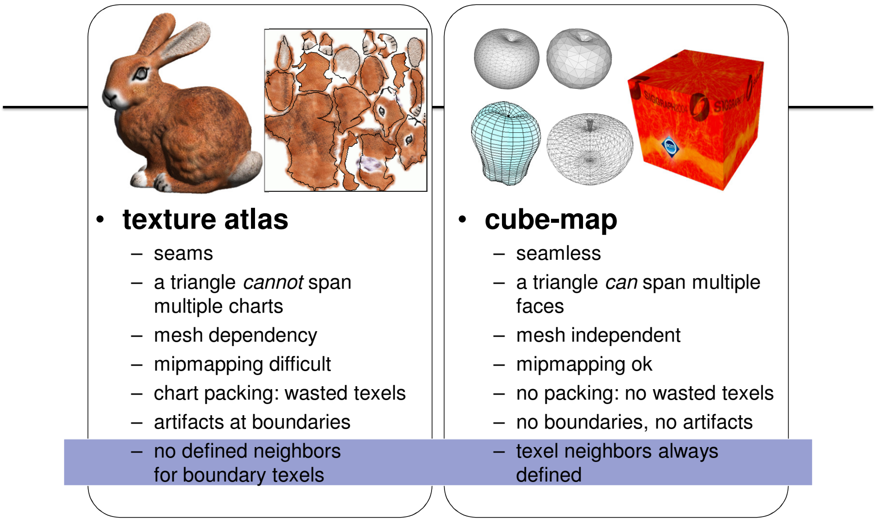

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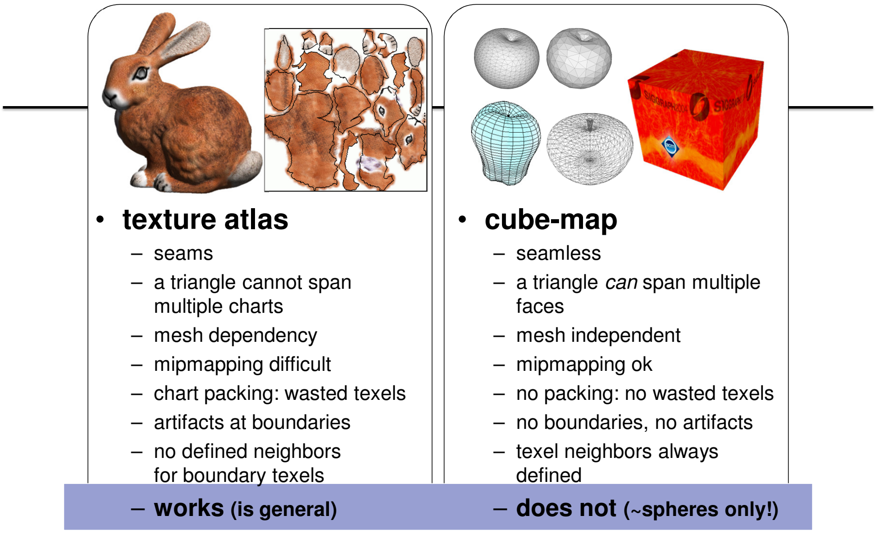
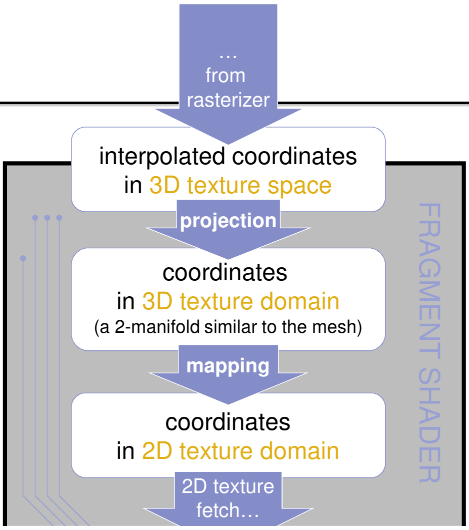


- **texture atlas**
  - seams
  - a triangle cannot span multiple charts
  - mesh dependency
  - mipmapping difficult
  - chart packing: wasted texels
  - artifacts at boundaries
  - no defined neighbors for boundary texels
  - **works (is general)**
- **cube-map**
  - seamless
  - a triangle *can* span multiple faces
  - mesh independent
  - mipmapping ok
  - no packing: no wasted texels
  - no boundaries, no artifacts
  - texel neighbors always defined
  - **does not (~spheres only!)**

What to Keep from CubeMaps

- Texture defined in 3D *BUT* stored in 2D

- Per-fragment
- Hardware implemented



… from rasterizer

interpolated coordinates
in 3D texture space

projection

coordinates
in 3D texture domain
(a 2-manifold similar to the mesh)

mapping

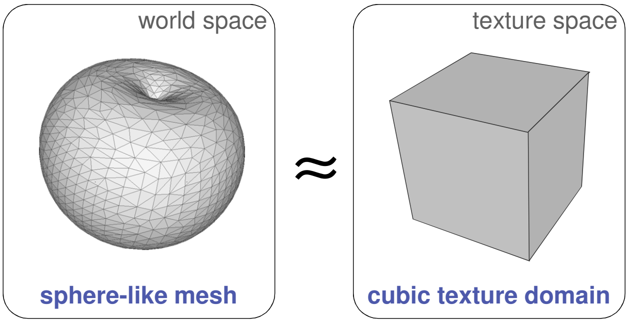
coordinates
in 2D texture domain

2D texture fetch…

FRAGMENT SHADER

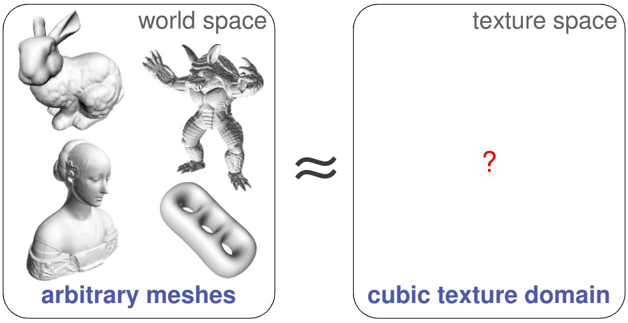
Going Beyond Apples

- Cube-Maps work well ***only*** for sphere-like objects



Going Beyond Apples

- But for more general objects?



world space

arbitrary meshes

≈

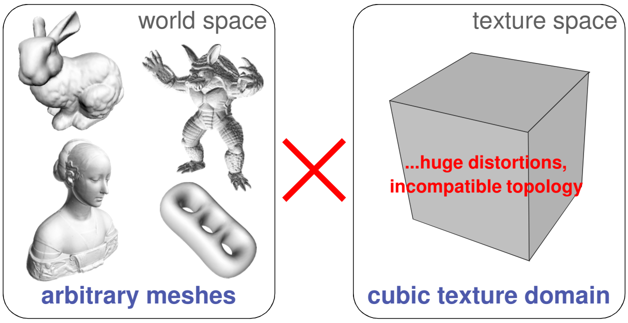
texture space

?

cubic texture domain

Going Beyond Apples

- But for more general objects?



world space

arbitrary meshes

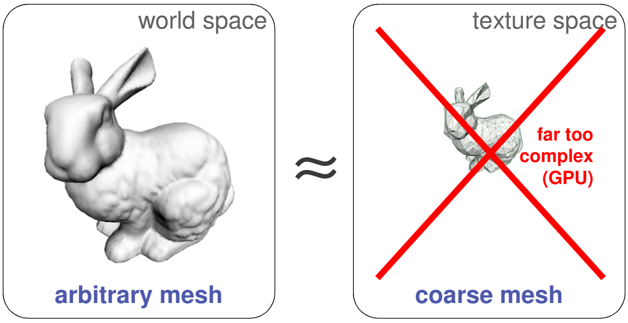
texture space

...huge distortions, incompatible topology

cubic texture domain

Going Beyond Apples

- But for more general objects?


world space

arbitrary mesh

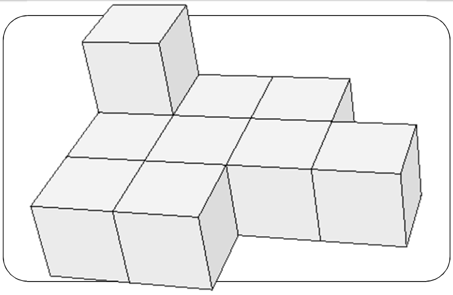
≈

texture space

far too complex (GPU)

coarse mesh

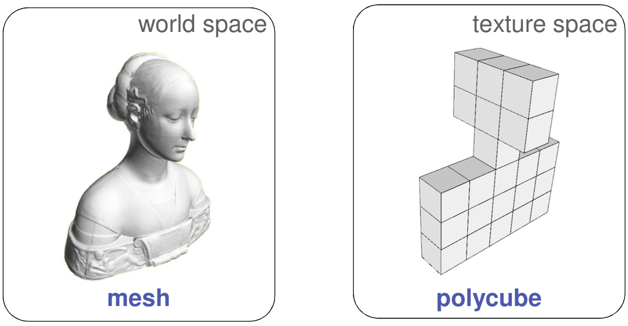
Introducing Polycubes



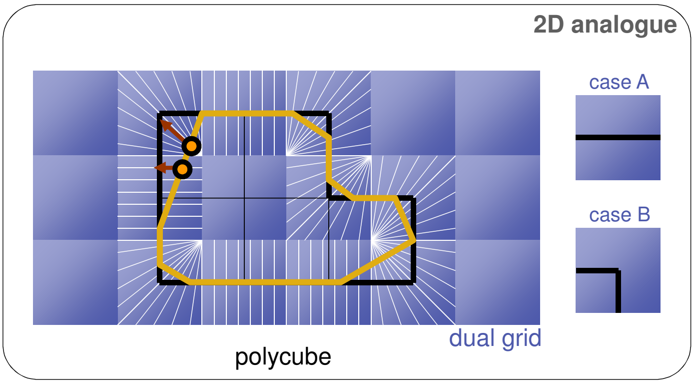
Po·ly·cube: *n. (Geom.)* A solid composed by multiple unit cubes attached face to face

Choosing a Polycube

- Polycube should *roughly* resemble the mesh

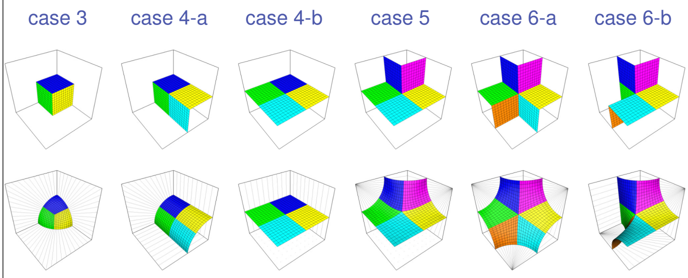


Partition of Texture Space



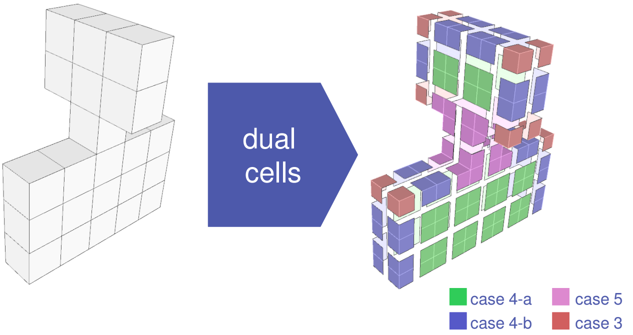
partition of the parameter space

back to 3D

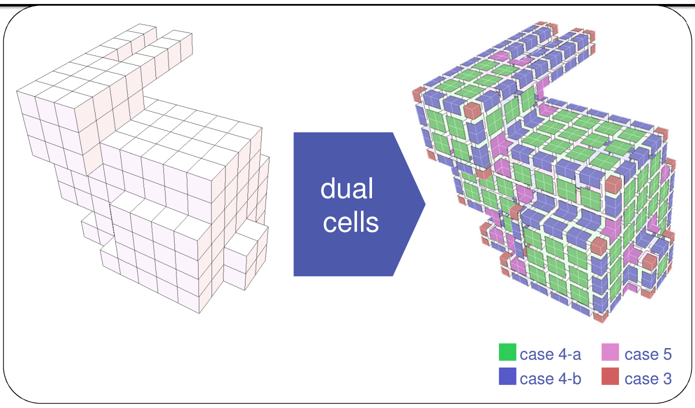


partition of the parameter space

back to 3D



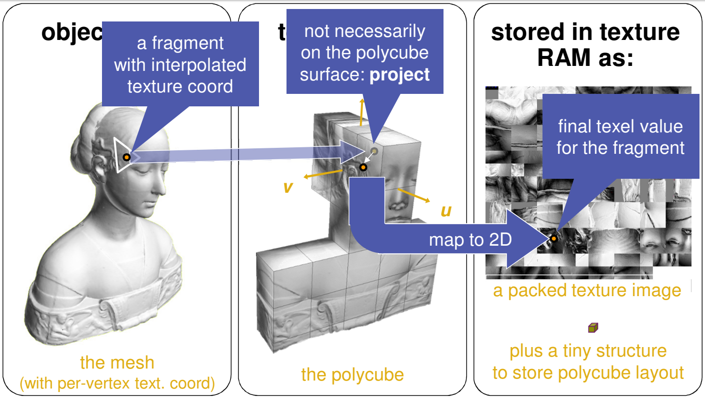
Partition of the Parameter Space



dual cells

🟩 case 4-a
🟪 case 5
🟦 case 4-b
🟥 case 3

PolyCube-Maps in a Nutshell



objec

a fragment with interpolated texture coord

the mesh
(with per-vertex text. coord)

t

not necessarily on the polycube surface: **project**

map to 2D

the polycube

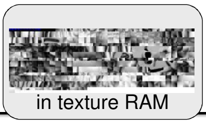
stored in texture RAM as:

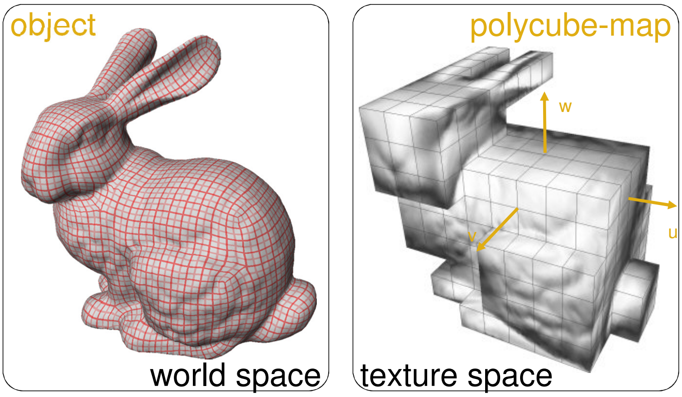
final texel value for the fragment

a packed texture image

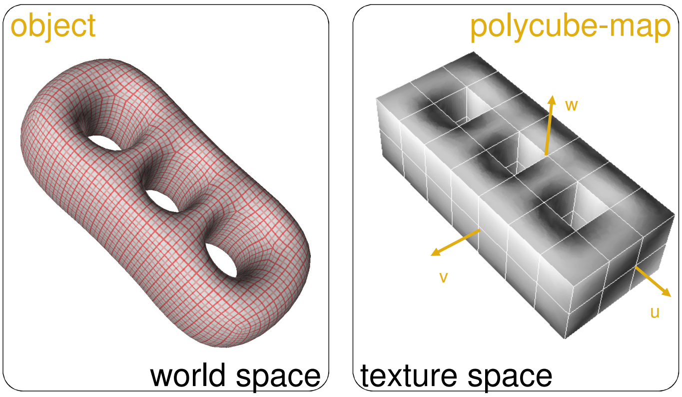
plus a tiny structure to store polycube layout

Examples of poly-cubic parameterizations

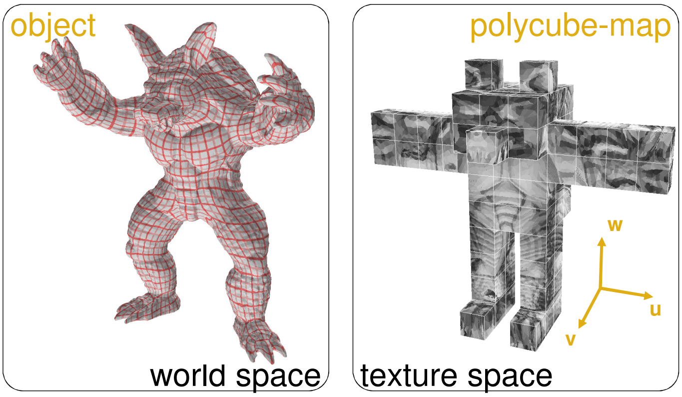




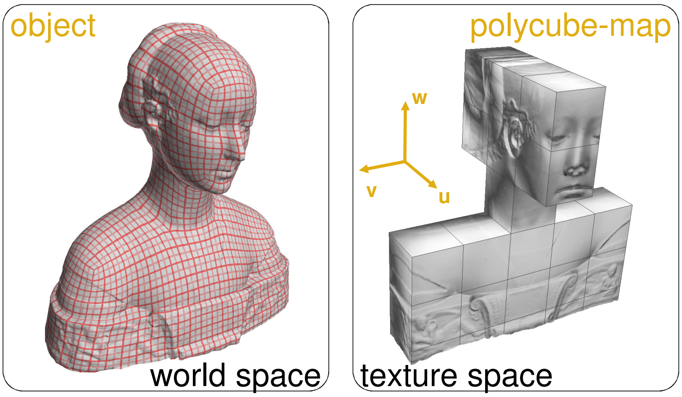
Examples of poly-cubic parameterizations

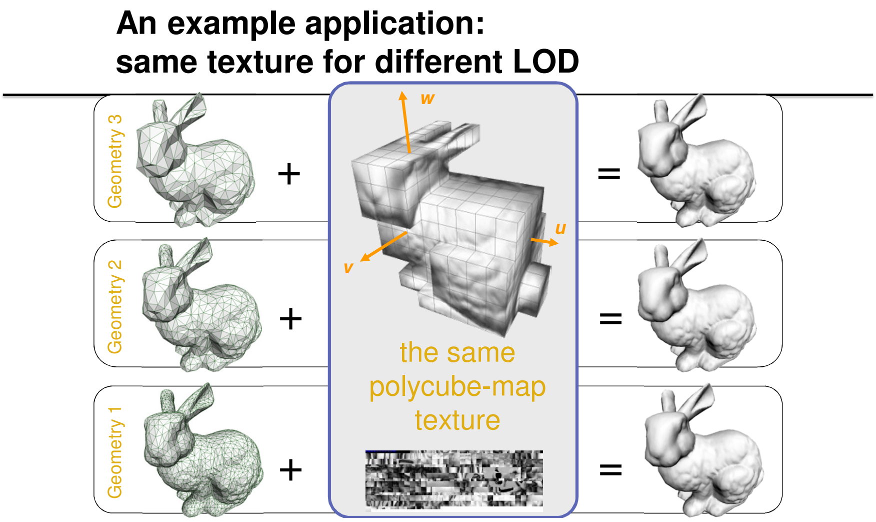


Examples of poly-cubic parameterizations

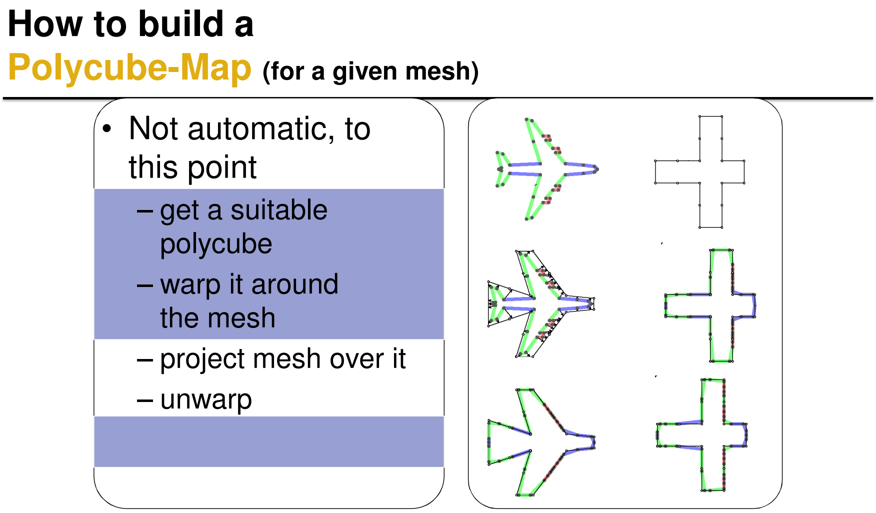


Examples of poly-cubic parameterizations





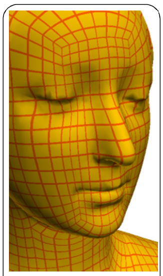
An example application: same texture for different LOD



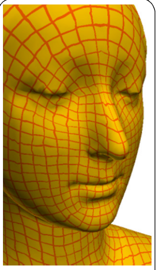
How to build a Polycube-Map (for a given mesh)

- Not automatic, to this point
  - get a suitable polycube
  - warp it around the mesh
  - project mesh over it
  - unwarp

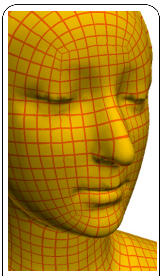
Global optimization



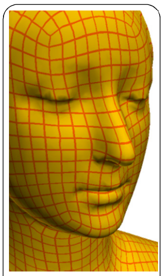
projection
(not optimized)



mean value



MIPS



ext. MIPS

Discussion

Pros

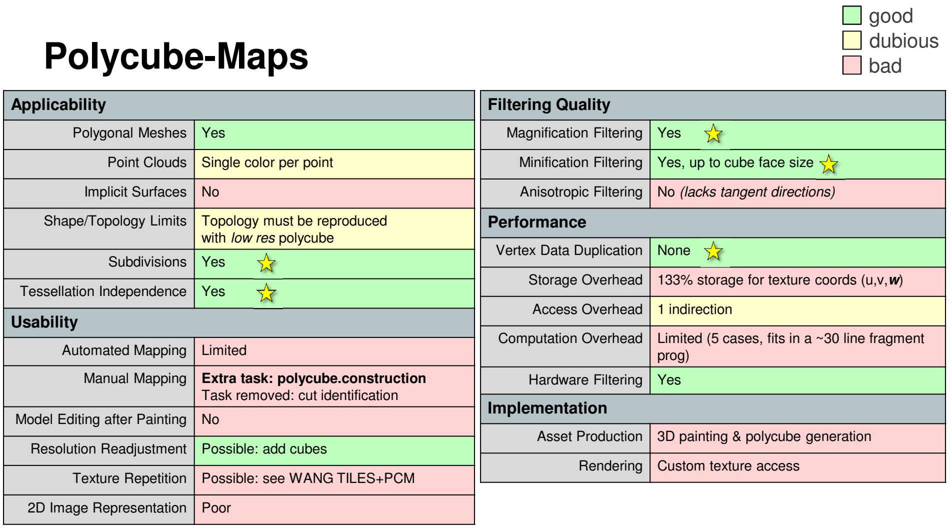
- truly seamless texture mapping
- no patch boundaries
- no color bleeding
- very low distortion
- nearly optimal texture packing
- bilinear filtering possible
- mipmapping possible
- mesh independency

Cons

- long fragment program
  - ~60 GPU instruction long
  - could be improved, with little branching support
- 3 t-coords per vertex
  - instead of 2

Limits

- cannot handle arbitrary shape/topology complexity
  - e.g. a tree



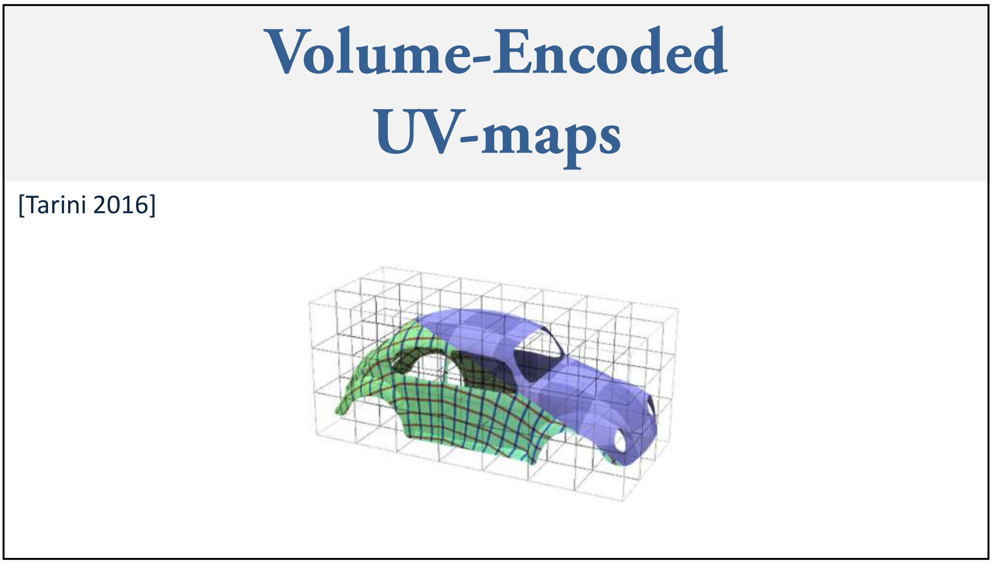
🟩 good
🟨 dubious
🟥 bad

Polycube-Maps

Applicability	
Polygonal Meshes	Yes
Point Clouds	Single color per point
Implicit Surfaces	No
Shape/Topology Limits	Topology must be reproduced with *low res* polycube
Subdivisions	Yes ☆
Tessellation Independence	Yes ☆
Usability	
Automated Mapping	Limited
Manual Mapping	**Extra task: polycube.construction** Task removed: cut identification
Model Editing after Painting	No
Resolution Readjustment	Possible: add cubes
Texture Repetition	Possible: see WANG TILES+PCM
2D Image Representation	Poor

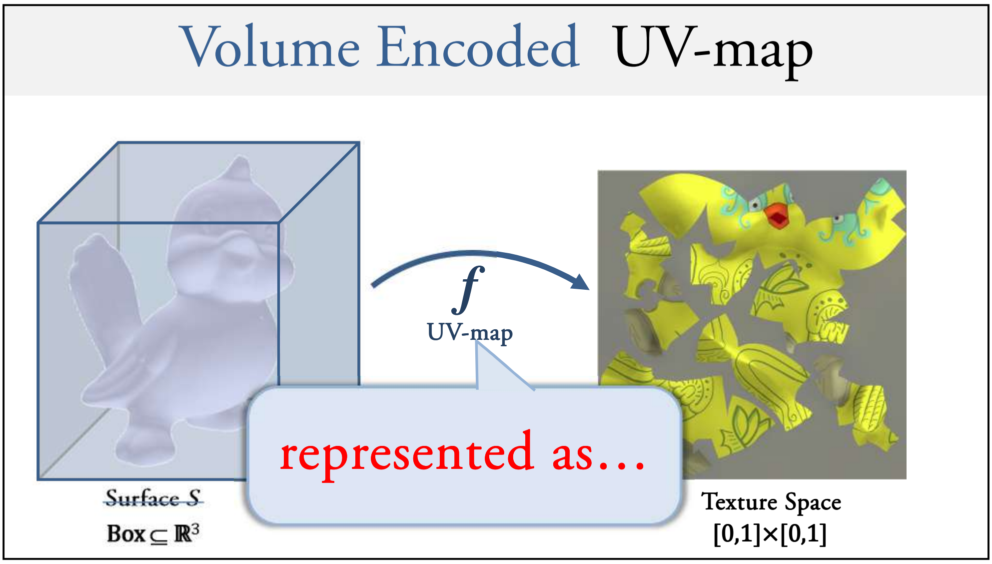
Filtering Quality	
Magnification Filtering	Yes ☆
Minification Filtering	Yes, up to cube face size ☆
Anisotropic Filtering	No *(lacks tangent directions)*
Performance	
Vertex Data Duplication	None ☆
Storage Overhead	133% storage for texture coords (u,v,***w***)
Access Overhead	1 indirection
Computation Overhead	Limited (5 cases, fits in a ~30 line fragment prog)
Hardware Filtering	Yes
Implementation	
Asset Production	3D painting & polycube generation
Rendering	Custom texture access

7.3 Volume-encoded UV-Maps



Volume-Encoded UV-maps

[Tarini 2016]



Volume Encoded UV-map

f

UV-map

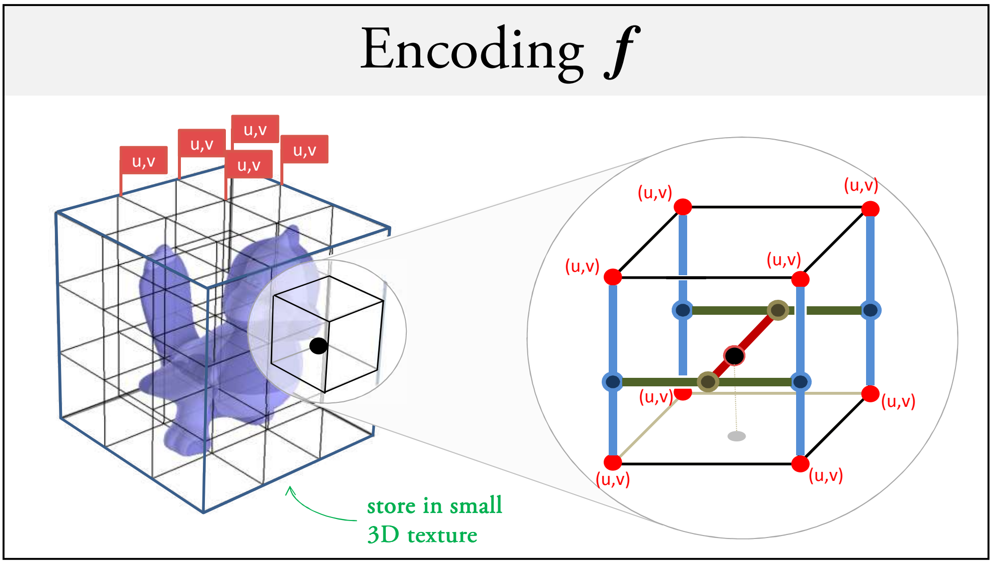
represented as…

~~Surface S~~

Box $\subseteq \mathbb{R}^3$

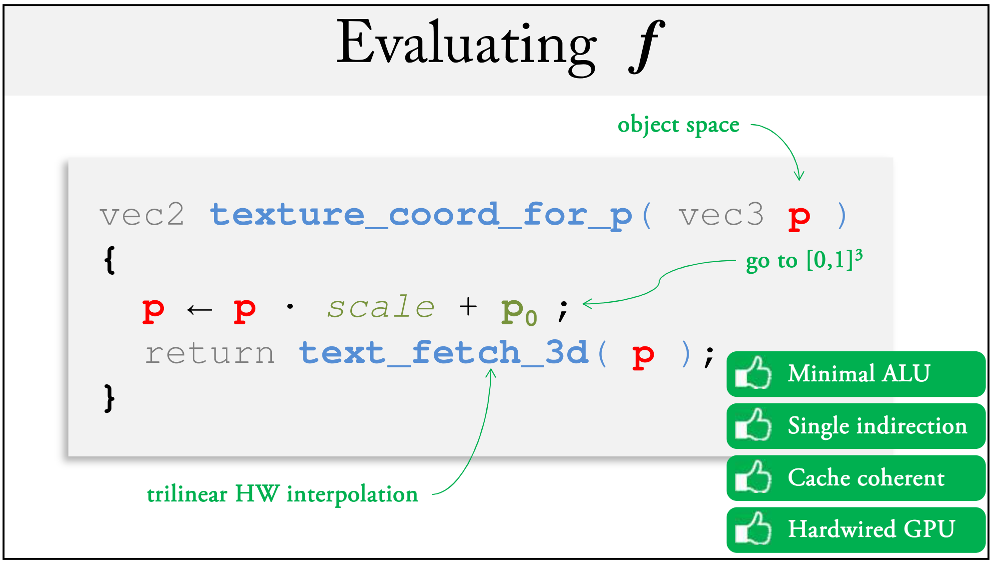
Texture Space

$[0,1]\times[0,1]$



Encoding f

store in small 3D texture



Evaluating f

object space

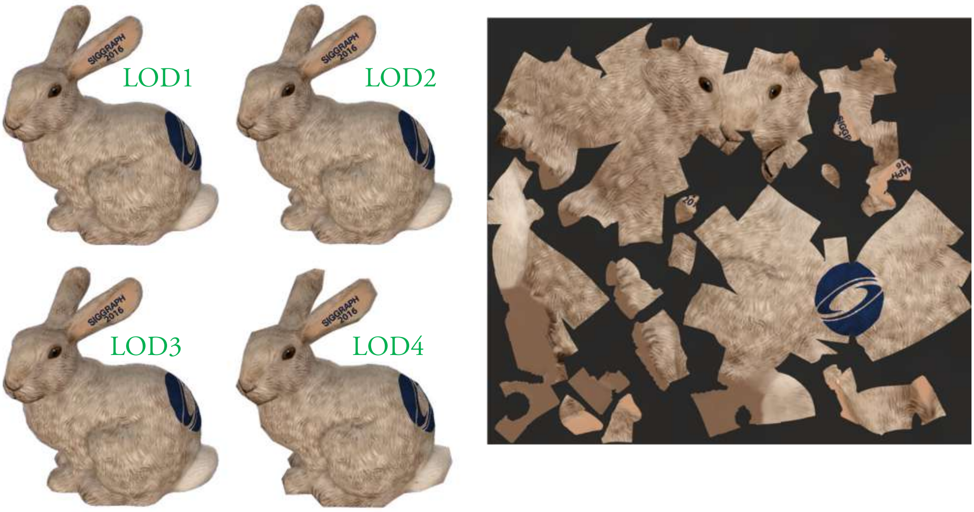
```
vec2 texture_coord_for_p( vec3 p )
{
  p ← p · scale + p0 ;
  return text_fetch_3d( p );
}
```

go to $[0,1]^3$

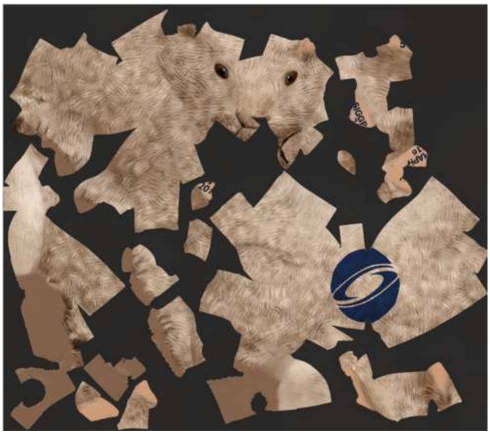
trilinear HW interpolation

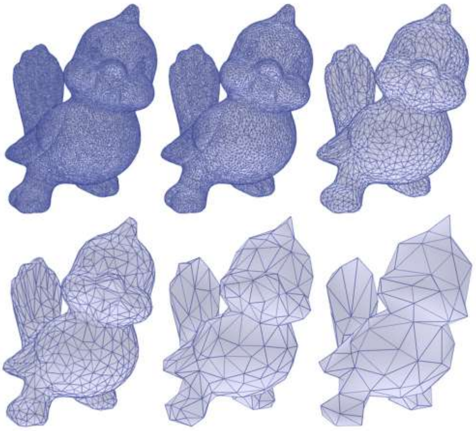
- Minimal ALU
- Single indirection
- Cache coherent
- Hardwired GPU

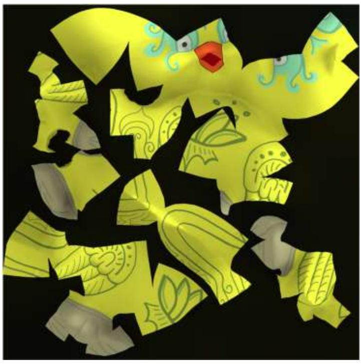
No vertex duplicates
No per-vert UV coords

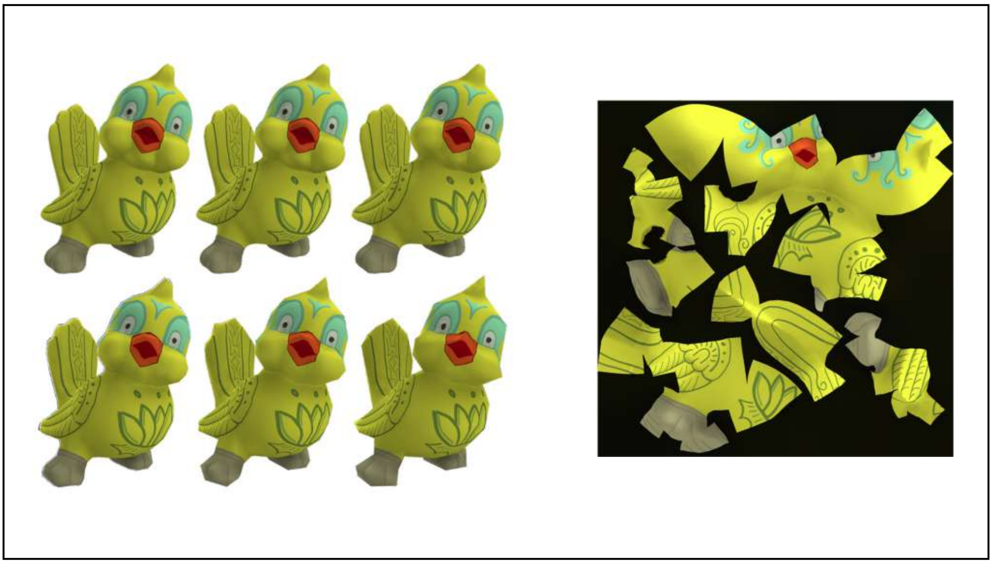


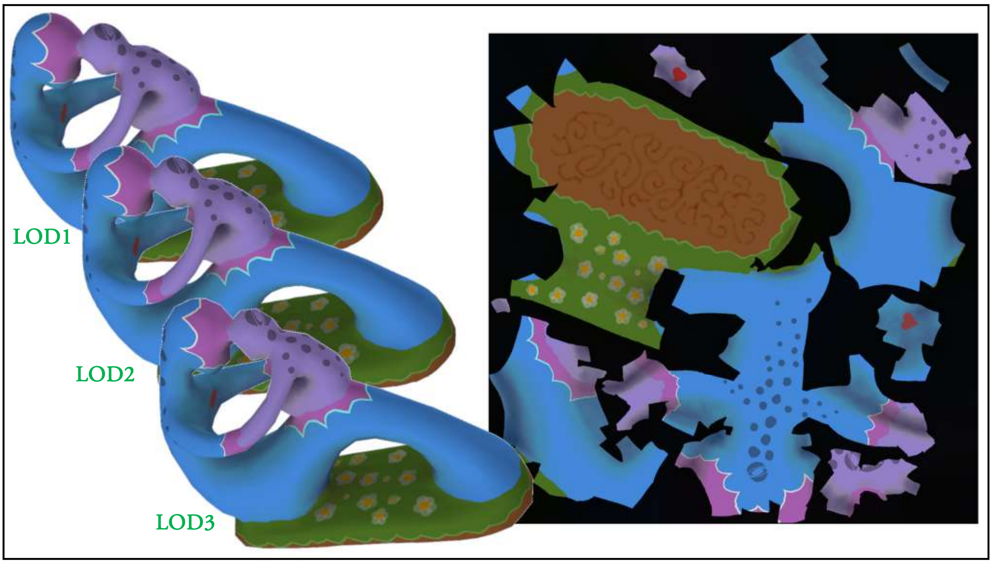
arbitrary remeshing
(here, quads)



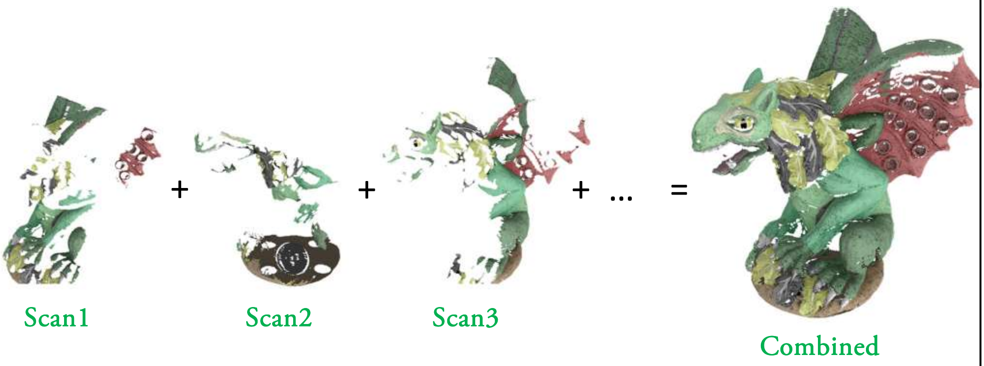


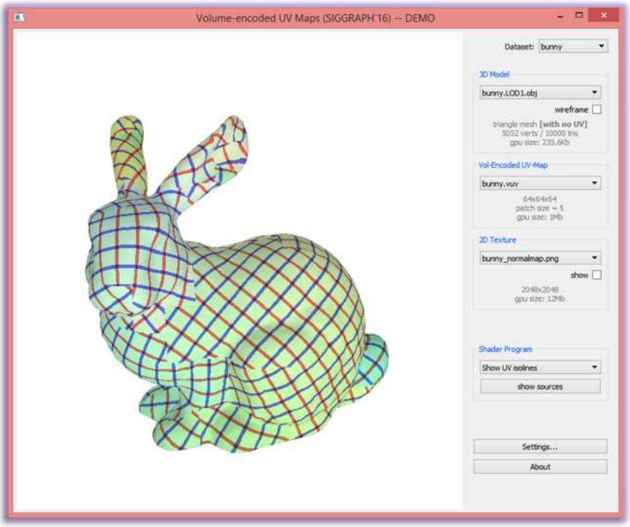





LOD1
LOD2
LOD3

Range scans




Volume-encoded UV Maps (SIGGRAPH'16) -- DEMO

Dataset: bunny

3D Model

bunny.LOD1.obj

wireframe ☐

triangle mesh **[with no UV]**
5052 verts / 10000 tris
gpu size: 235.6kb

Vol-Encoded UV-Map

bunny.vuv

64x64x64
patch size = 5
gpu size: 1Mb

2D Texture

bunny_normalmap.png

show ☐

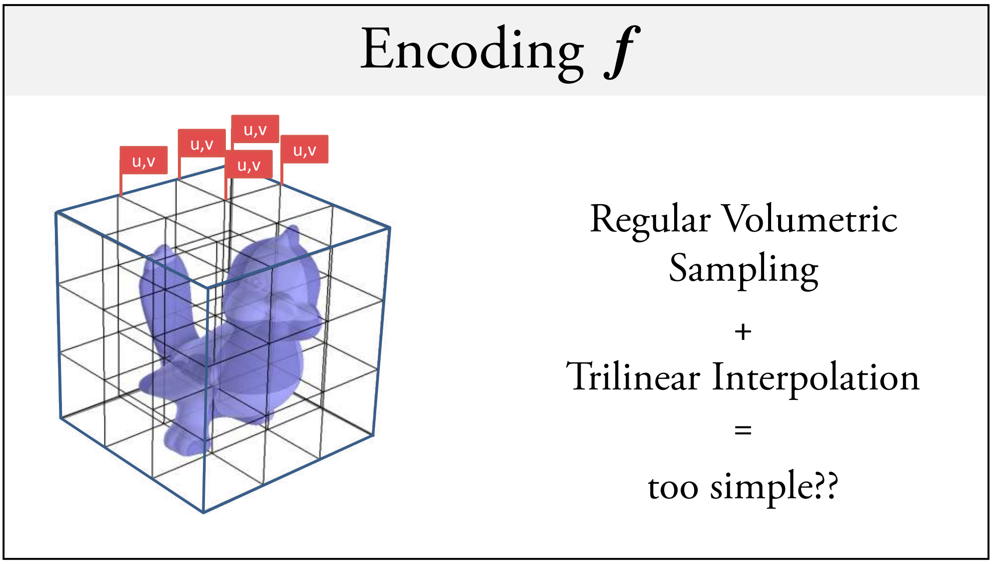
2048x2048
gpu size: 12Mb

Shader Program

Show UV isolines

Try
our
demo!

google for:
Volume Encoded
UV-maps



Encoding f

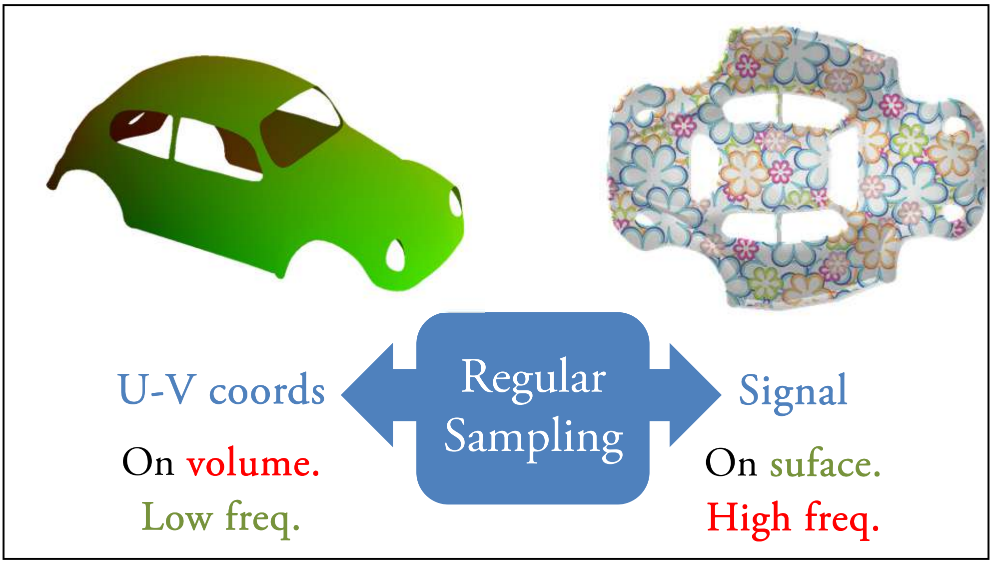
Regular Volumetric Sampling

+

Trilinear Interpolation

=

too simple??



U-V coords

On volume.

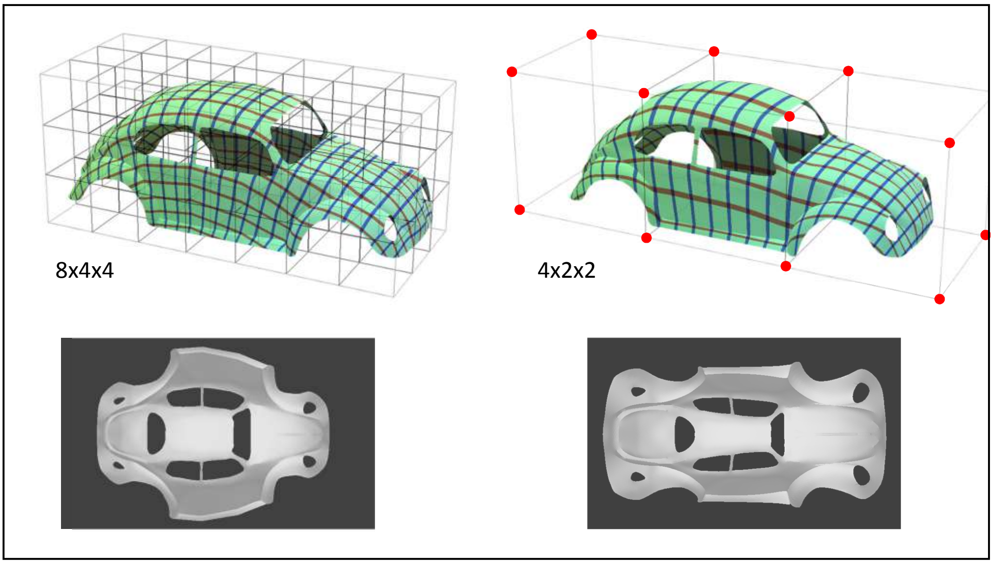
Low freq.

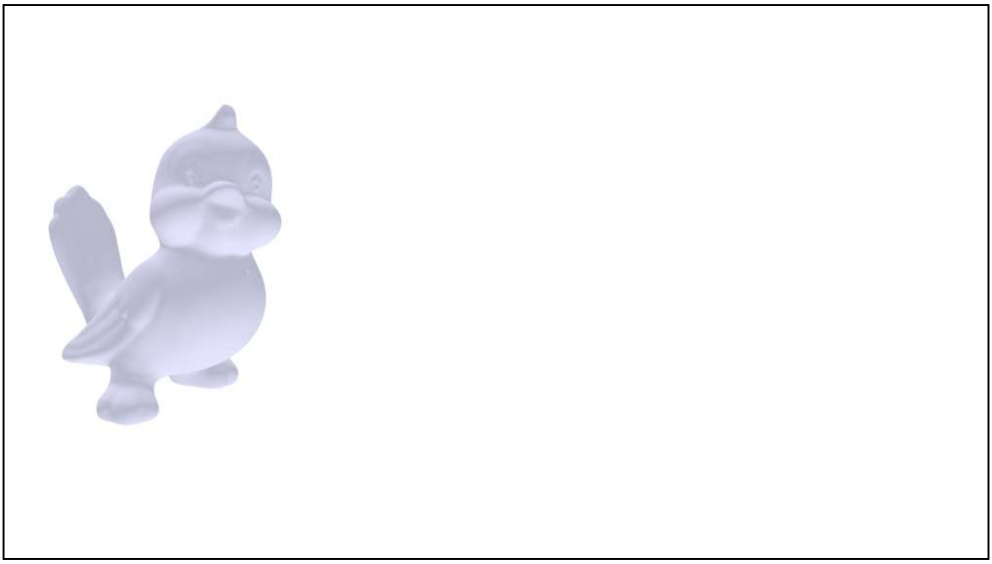
Regular Sampling

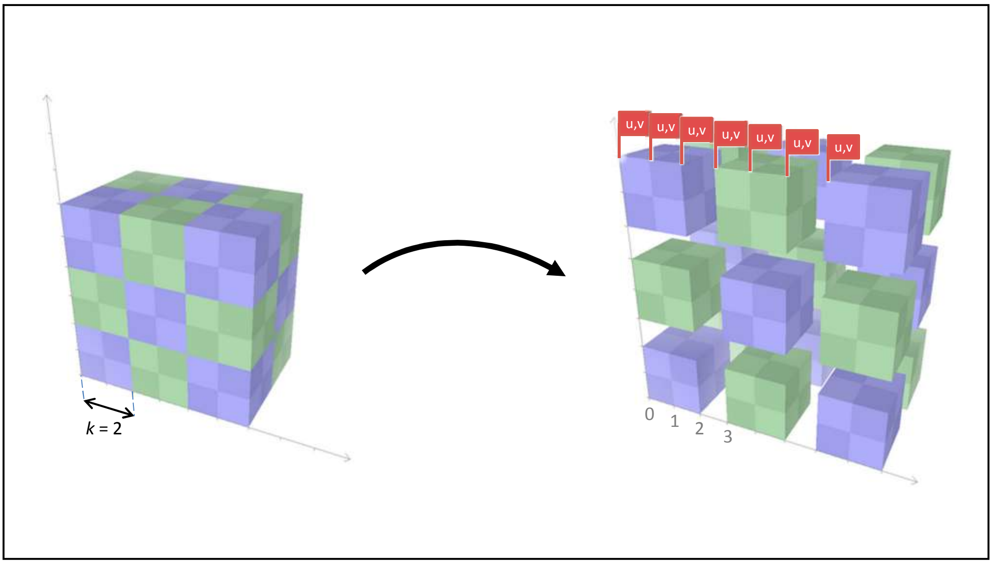
Signal

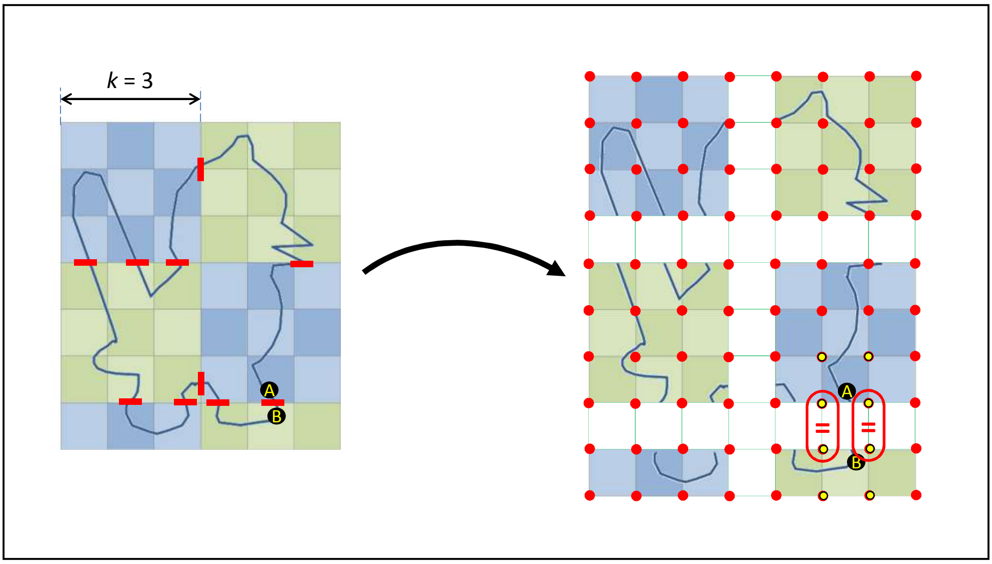
On suface.

High freq.

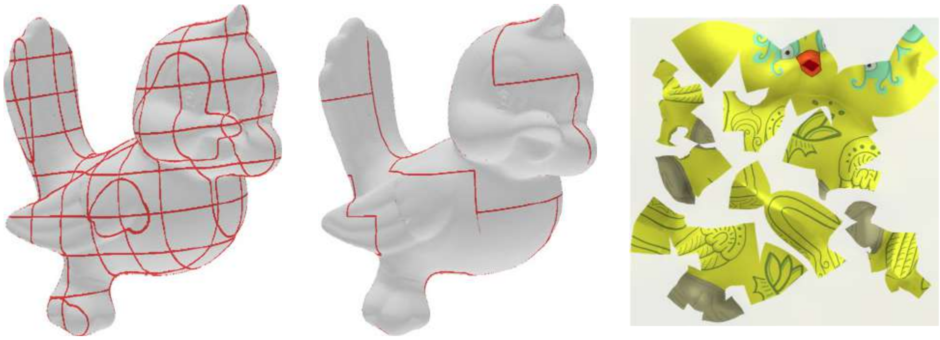

8x4x4
4x2x2



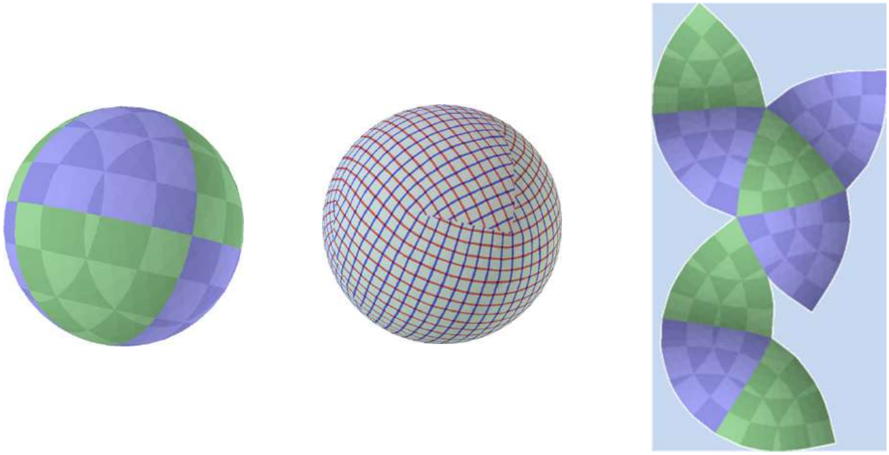

k = 2
u,v
u,v
u,v
u,v
u,v
u,v
u,v
0
1
2
3


k = 3
A
B
A
B
=
=

Volumetric UV-Maps: Cuts



Volumetric UV-Maps: Cuts

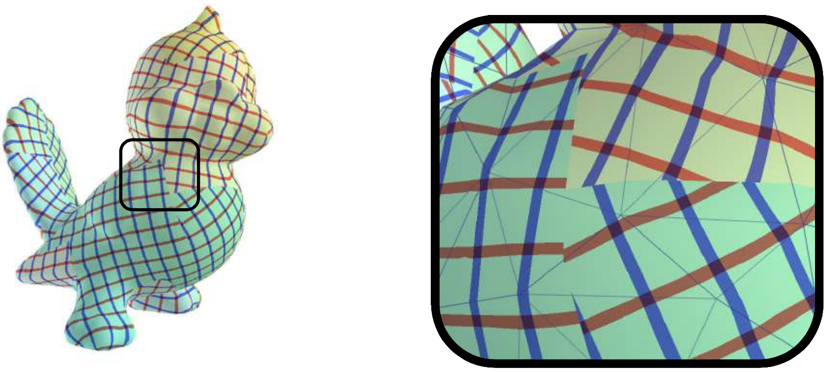


Adding discontinuities

```
texture_coord_for_p( vec3 p )
{
  p ← p · scale + $p_0$ ;
  p ← p + ⌊ p / k ⌋ ;
  return text_fetch_3d( p );
}
```

- 👍 Minimal ALU
- 👍 Single indirection
- 👍 Cache coherent
- 👍 Hardwired GPU

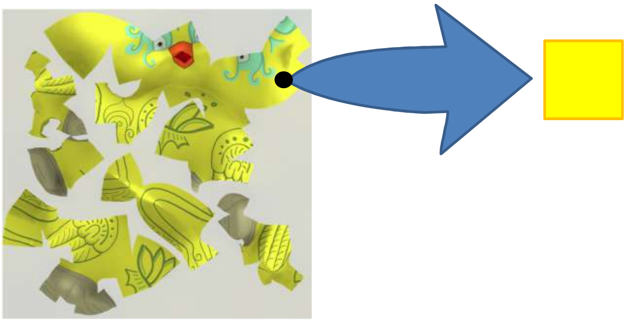
Cuts are Volumetric too!

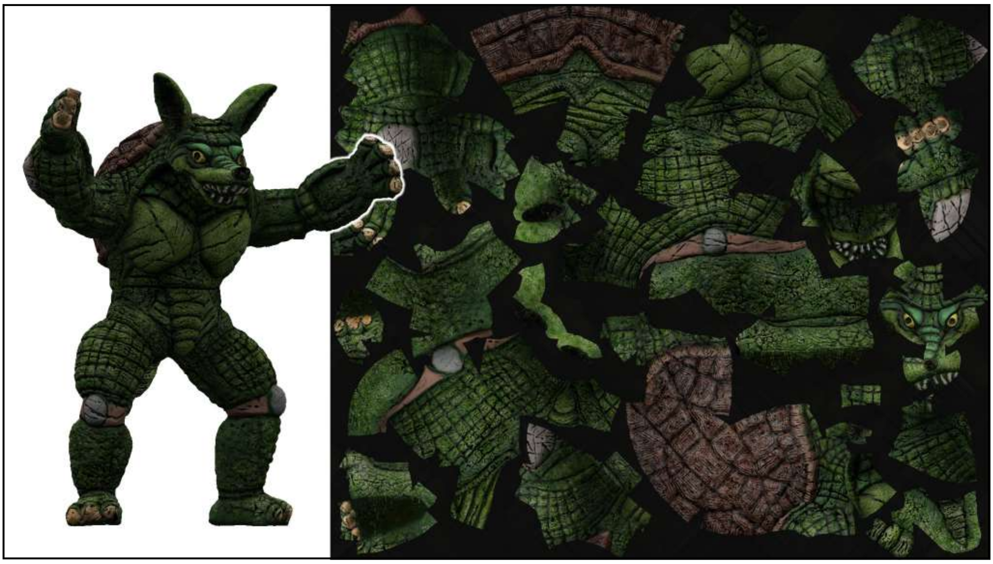


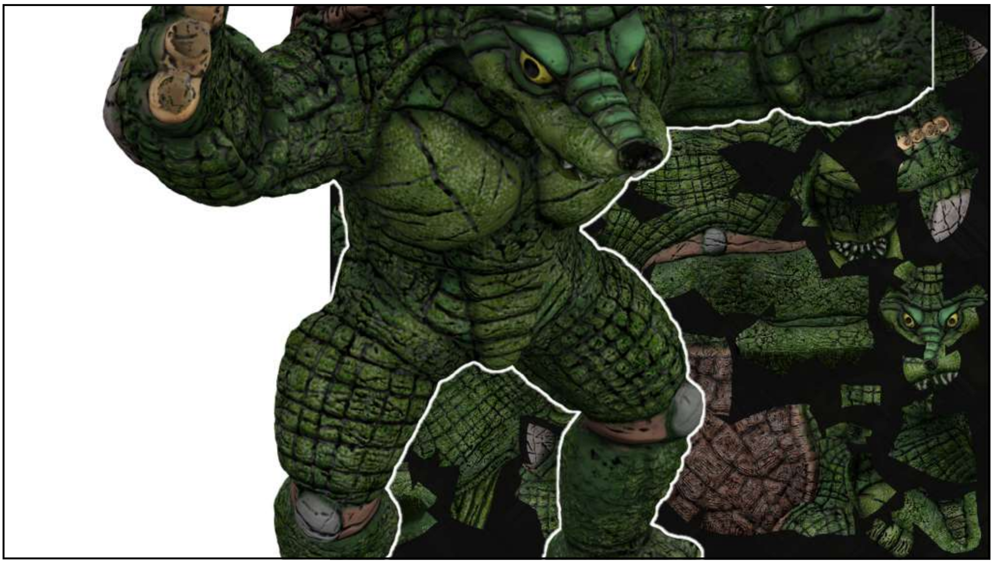
Using Vol-Encoded UV-maps

```
text_coord_for_p( vec3 p )
{
  p ← p · scale + $p_0$ ;
  p ← p + $\lfloor$ p / k $\rfloor$ ;
  return text_fetch_3d( p );
}
```

Final 2D texture access





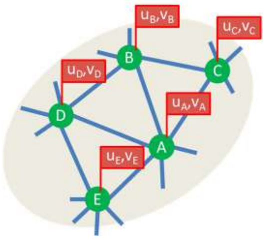



Bilinear Interpolation

Texture Repeat

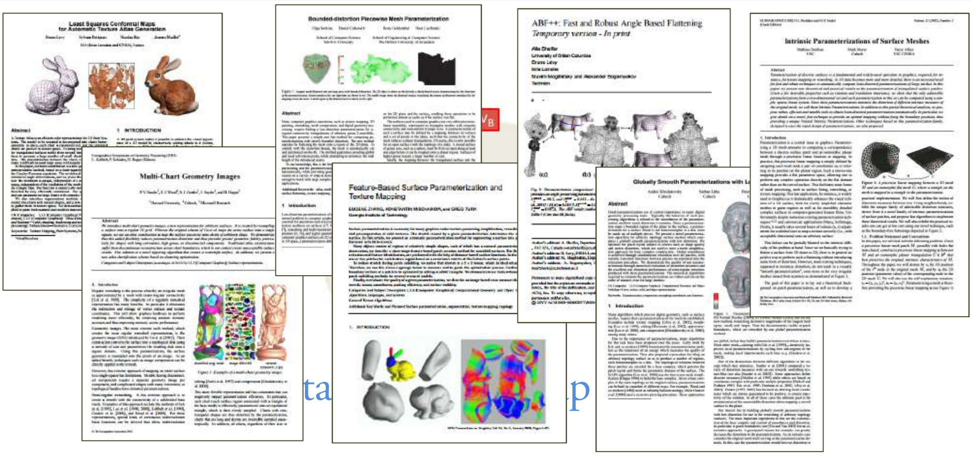
Construction
of
Volume Encoded UV-maps

Volume-Encoded UV-maps: construction



Standard UV-map

Volume-Encoded UV-maps: construction



Least Squares Conformal Maps for Automatic Texture Atlas Generation

Bounded-distortion Piecewise Mesh Parameterization

ABF++: Fast and Robust Angle Based Flattening

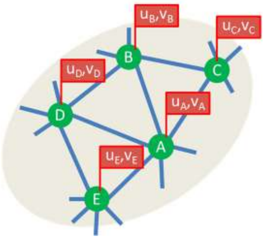
Intrinsic Parameterizations of Surface Meshes

Multi-Chart Geometry Images

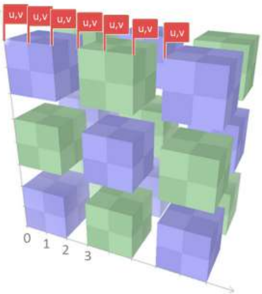
Feature-Based Surface Parameterization and Texture Mapping

Globally Smooth Parameterizations with L

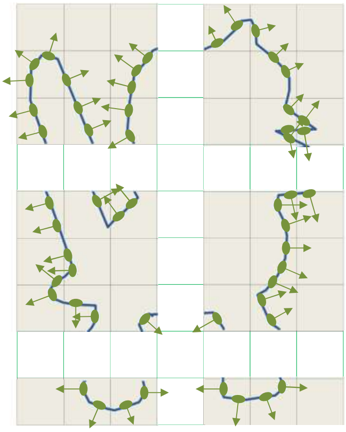
Volume-Encoded UV-maps: construction

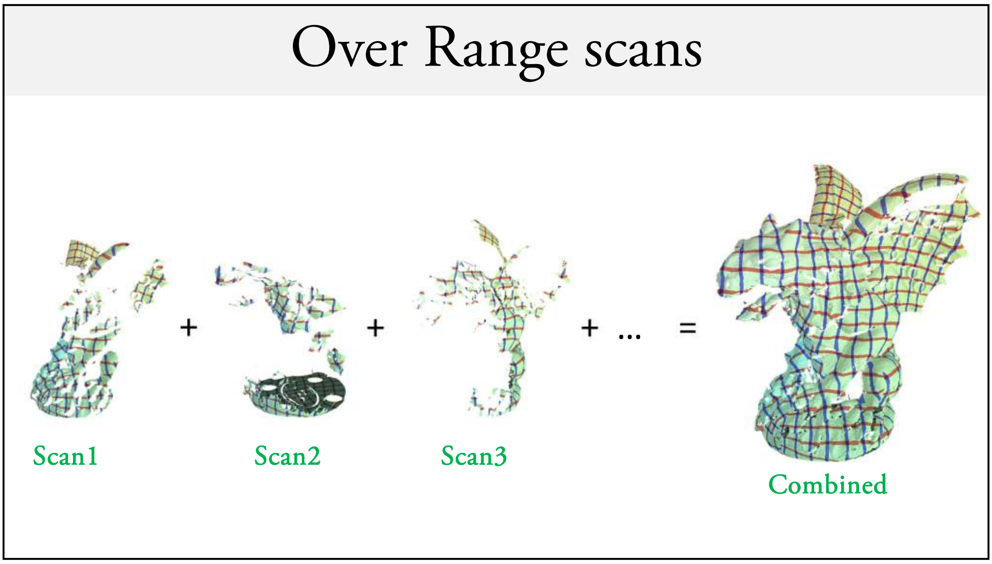


Standard
UV-map

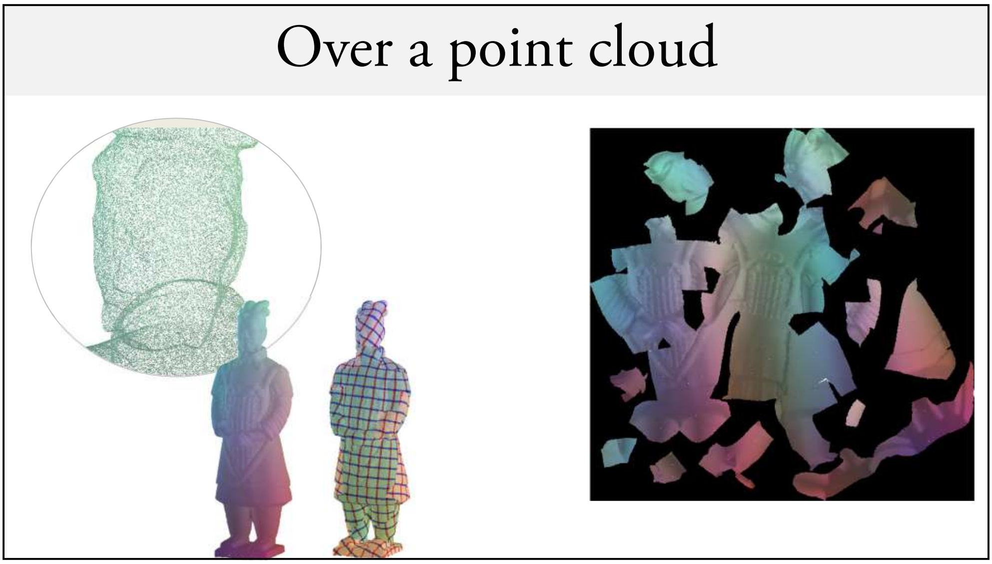


Vol-Encoded
UV-map

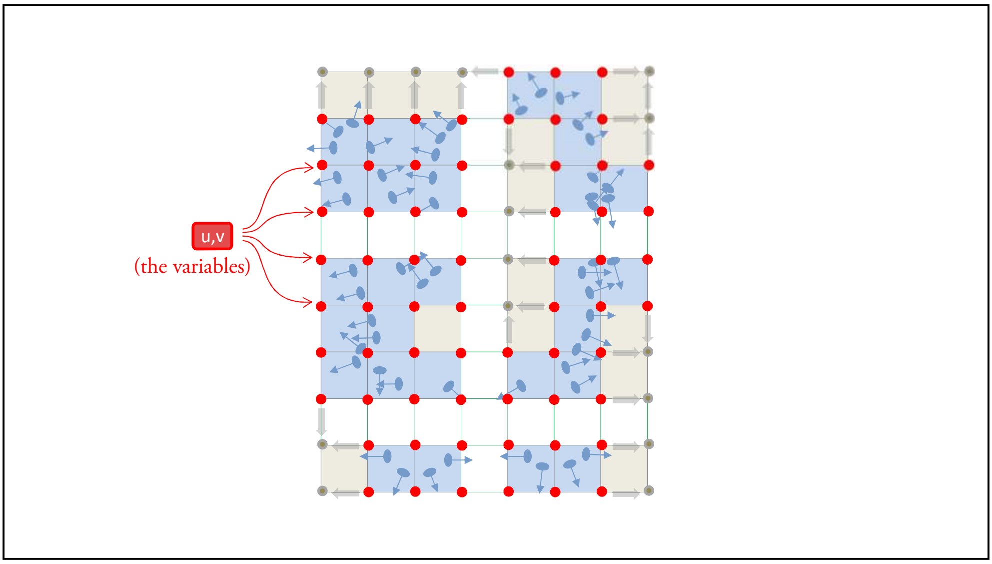


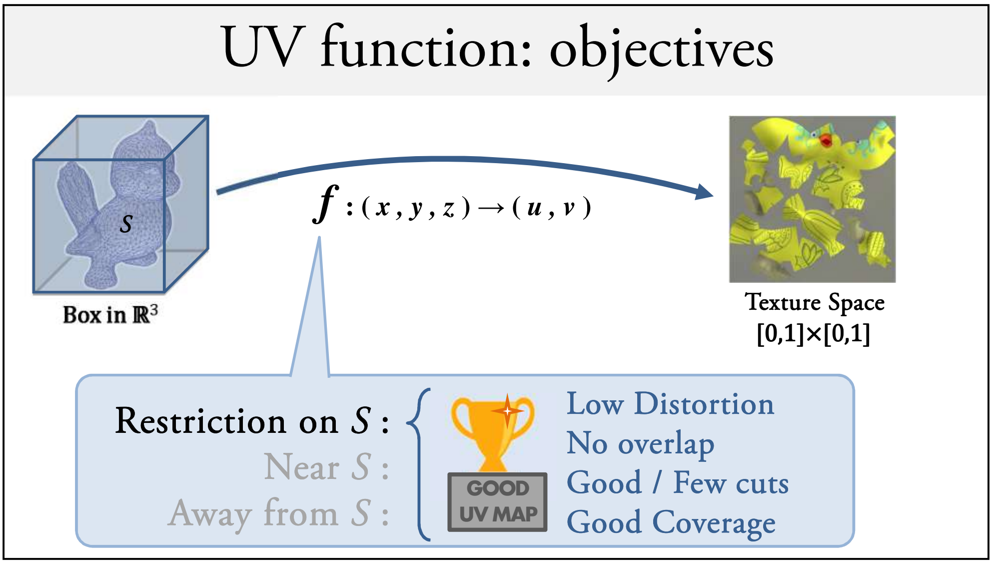


Over Range scans



Over a point cloud





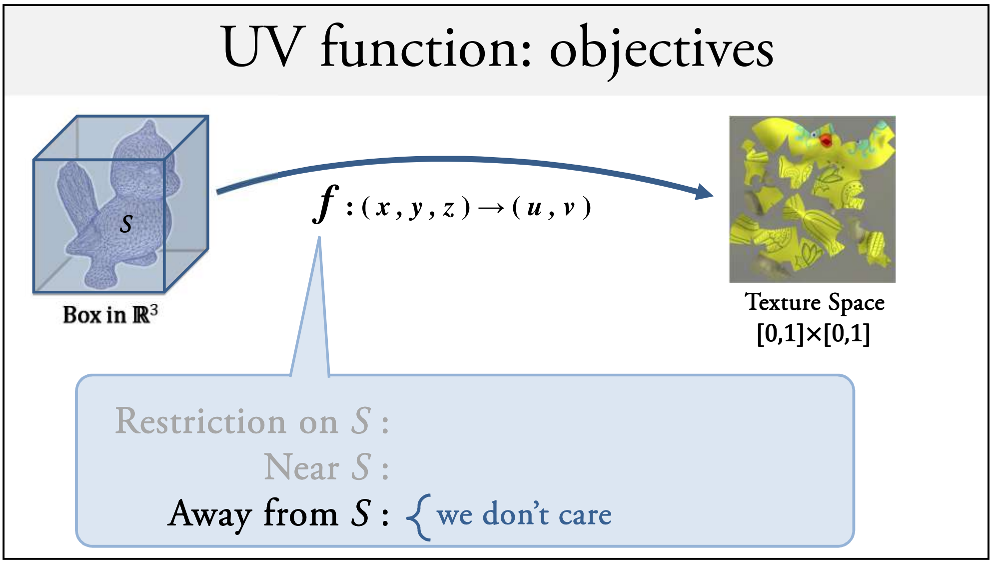
UV function: objectives

$f : (x, y, z) \rightarrow (u, v)$

Texture Space
$[0,1] \times [0,1]$

Restriction on S :
Near S :
Away from S :

Low Distortion
No overlap
Good / Few cuts
Good Coverage



UV function: objectives

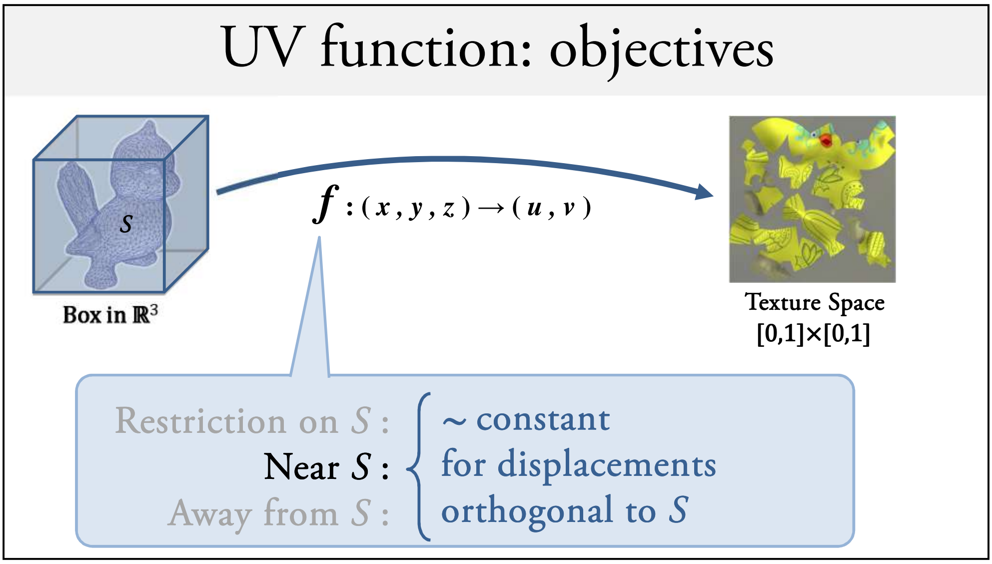
S

Box in $\mathbb{R}^3$

$f:(x,y,z)\rightarrow(u,v)$

Texture Space
[0,1]×[0,1]

Restriction on S :
Near S :
Away from S : $\{$ we don't care



UV function: objectives

S

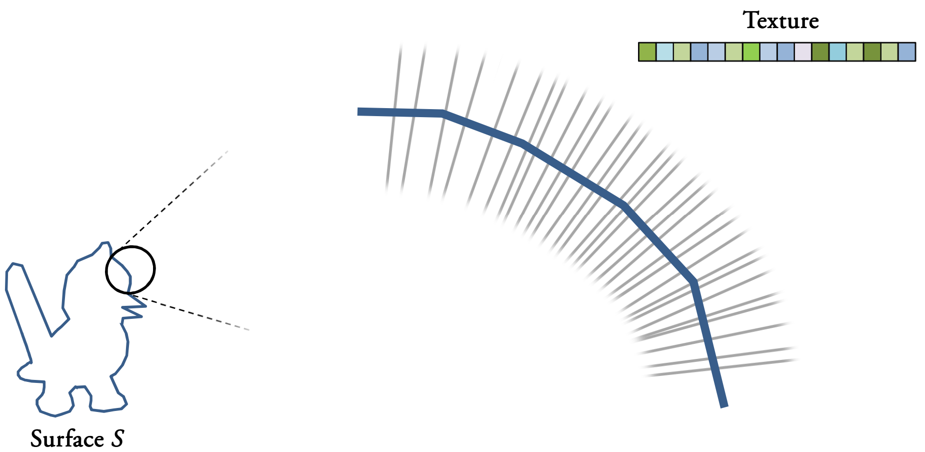
Box in $\mathbb{R}^3$

$f:(x,y,z)\rightarrow(u,v)$

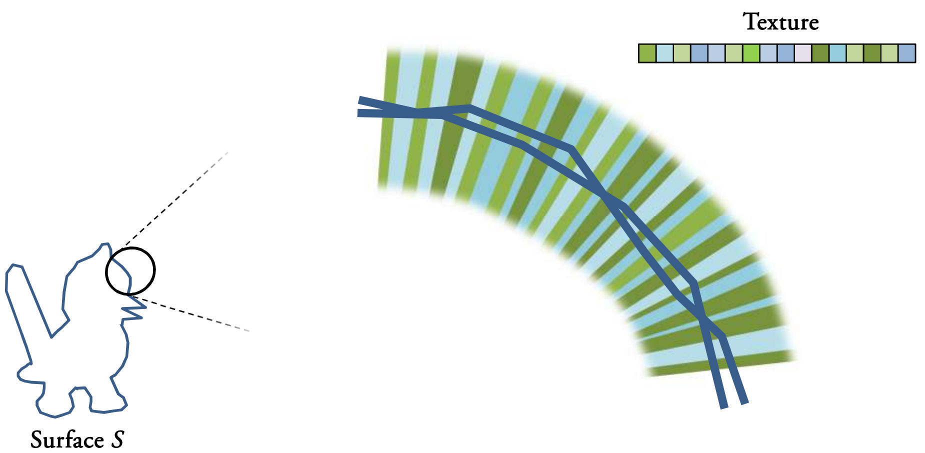
Texture Space
[0,1]×[0,1]

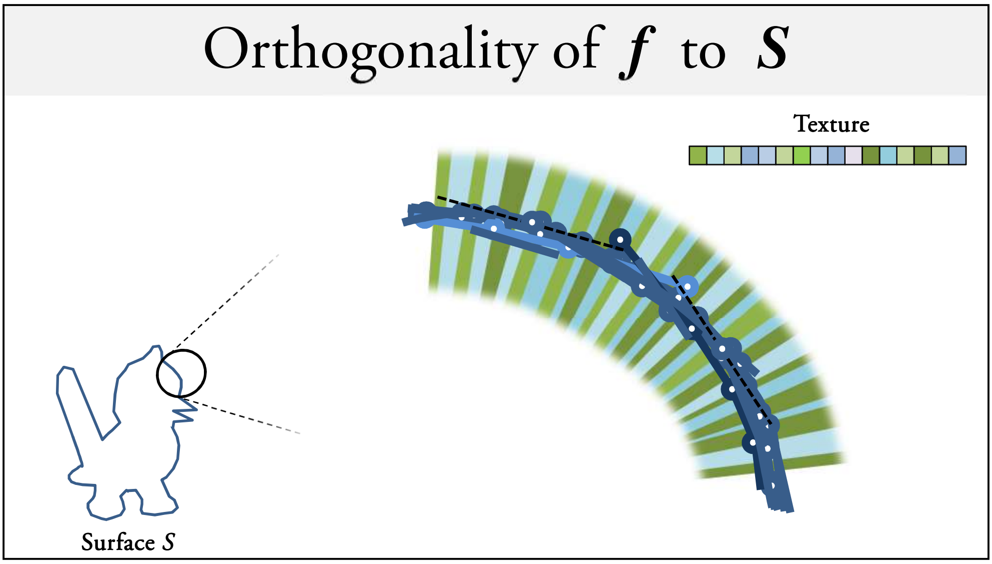
Restriction on S :
Near S : $\left\{\begin{array}{l}\sim \text{constant} \\ \text{for displacements} \\ \text{orthogonal to } S\end{array}\right.$
Away from S :

Orthogonality of f to S

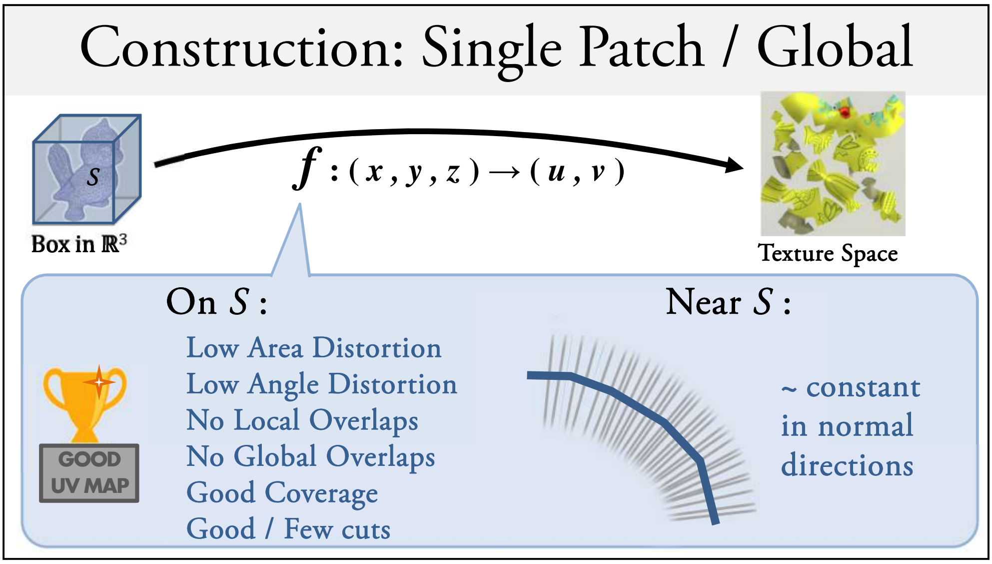


Orthogonality of f to S





Orthogonality of f to S



Construction: Single Patch / Global

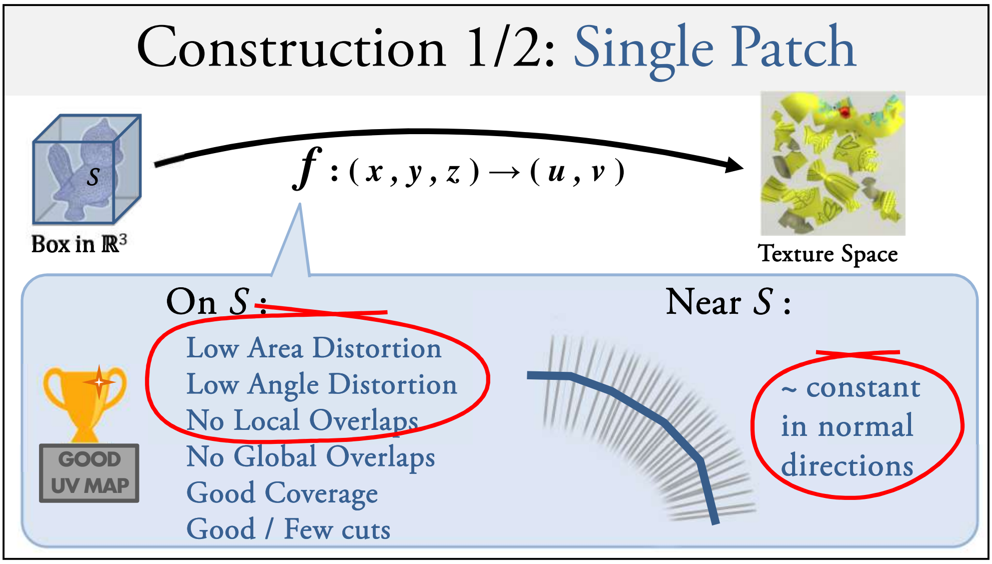
$f : (x, y, z) \rightarrow (u, v)$

On S :

- Low Area Distortion
- Low Angle Distortion
- No Local Overlaps
- No Global Overlaps
- Good Coverage
- Good / Few cuts

Near S :

~ constant in normal directions



Construction 1/2: Single Patch

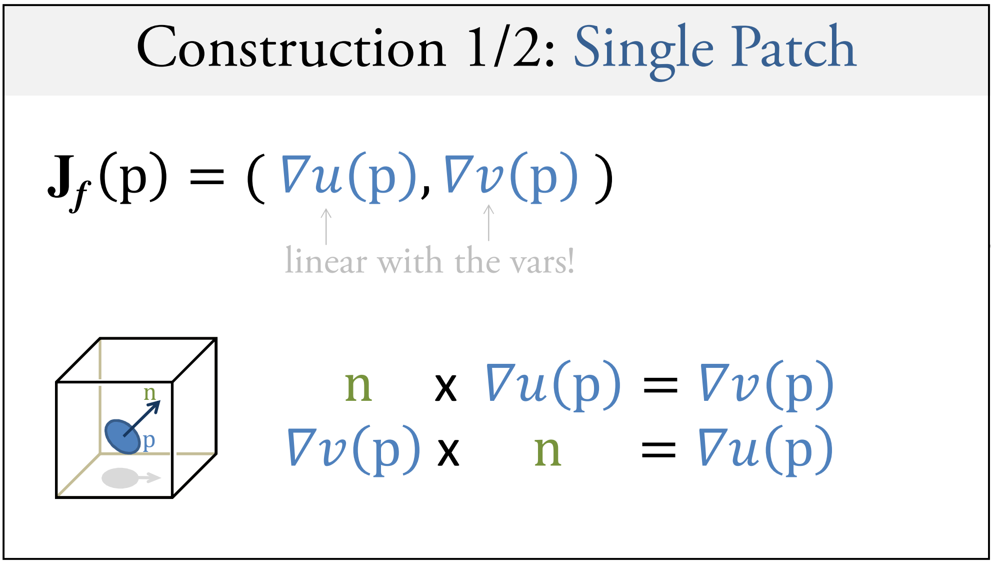
$f : (x, y, z) \rightarrow (u, v)$

On S :

- Low Area Distortion
- Low Angle Distortion
- No Local Overlaps
- No Global Overlaps
- Good Coverage
- Good / Few cuts

Near S :

~ constant in normal directions

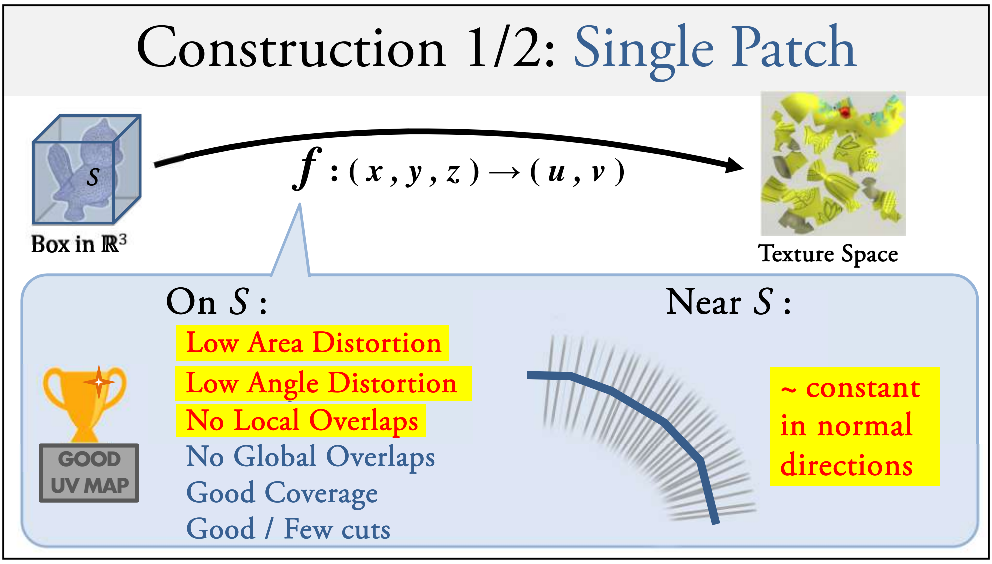


Construction 1/2: Single Patch

$$\mathbf{J}_f(\mathrm{p}) = (\, \nabla u(\mathrm{p}), \nabla v(\mathrm{p}) \,)$$

linear with the vars!

$$\mathrm{n} \times \nabla u(\mathrm{p}) = \nabla v(\mathrm{p})$$
$$\nabla v(\mathrm{p}) \times \mathrm{n} = \nabla u(\mathrm{p})$$



Construction 1/2: Single Patch

$$f : (x, y, z) \rightarrow (u, v)$$

Texture Space

On S :

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- No Global Overlaps
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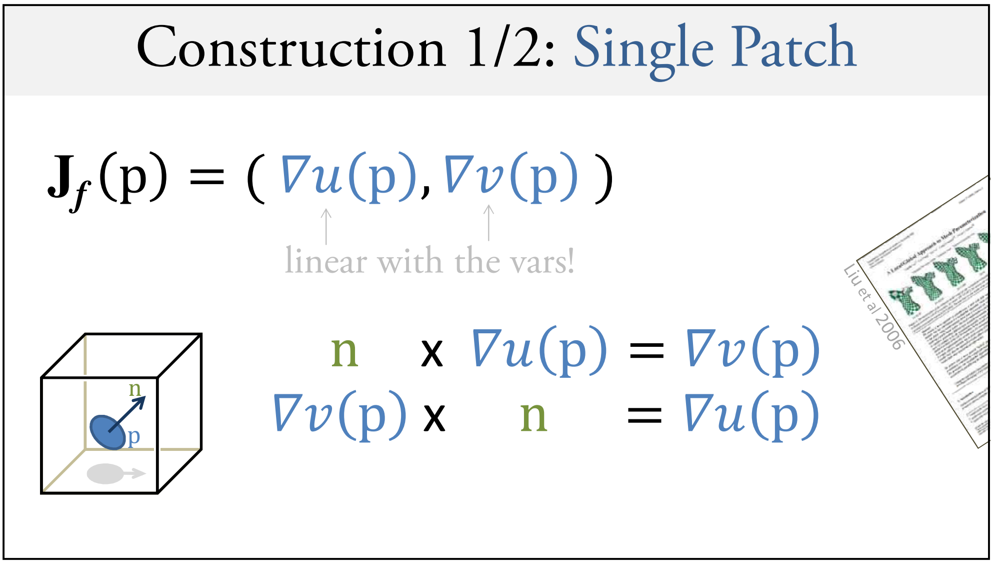
- Good / Few cuts

Near S :

~ constant in normal directions



Construction 1/2: Single Patch

$$\mathbf{J}_f(\mathrm{p}) = (\nabla u(\mathrm{p}), \nabla v(\mathrm{p}))$$

↑ ↑
linear with the vars!

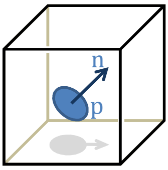
$$\mathrm{n} \times \nabla u(\mathrm{p}) = \nabla v(\mathrm{p})$$
$$\nabla v(\mathrm{p}) \times \mathrm{n} = \nabla u(\mathrm{p})$$

Liu et al 2006

Energy for Single Patch Construction

$$\mathbf{J}_f(\mathrm{p}) = (\, \underset{\uparrow}{\nabla} u(\mathrm{p}), \underset{\uparrow}{\nabla} v(\mathrm{p}) \,)$$

linear with the vars!



$$\mathrm{n} \times \nabla u(\mathrm{p}) = \nabla v(\mathrm{p})$$

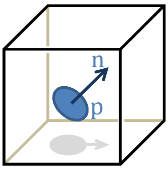
$$\nabla v(\mathrm{p}) \times \mathrm{n} = \nabla u(\mathrm{p})$$

$$\nabla u(\mathrm{p}) \times \nabla v(\mathrm{p}) = \mathrm{n} \cdot k_a$$

Energy for Single Patch Construction

$$\mathbf{J}_f(\mathrm{p}) = (\, \underset{\uparrow}{\nabla} u(\mathrm{p}), \underset{\uparrow}{\nabla} v(\mathrm{p}) \,)$$

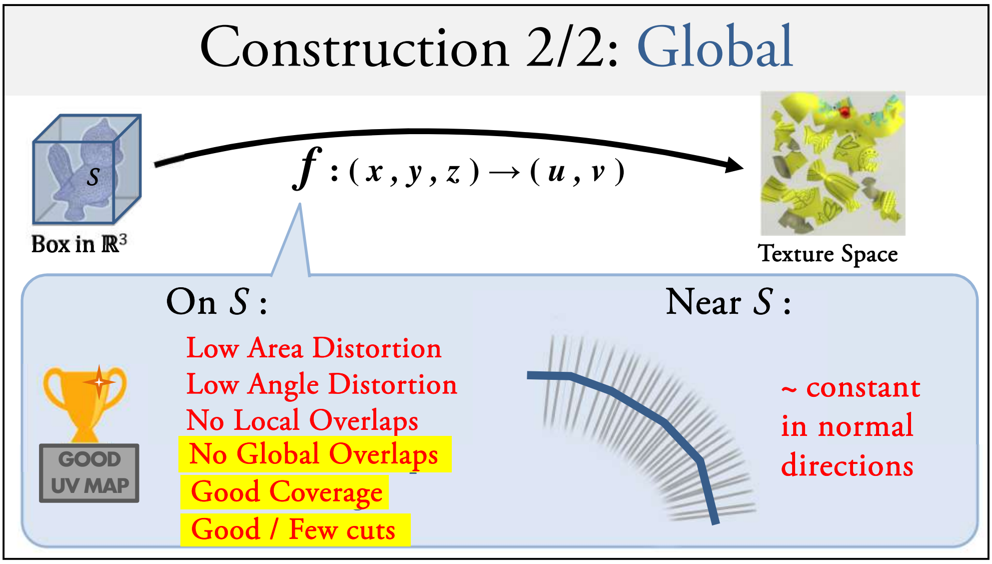
linear with the vars!



$$\| \mathrm{n} \times \nabla u(\mathrm{p}) - \nabla v(\mathrm{p}) \|_2^2$$

$$\| \nabla v(\mathrm{p}) \times \mathrm{n} - \nabla u(\mathrm{p}) \|_2^2$$

$$\| \nabla u(\mathrm{p}) \times \nabla v(\mathrm{p}) - \mathrm{n} \cdot k_a \|_2^2$$



Construction 2/2: Global

$f : (x , y , z) \rightarrow (u , v)$

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- Low Angle Distortion
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- No Global Overlaps
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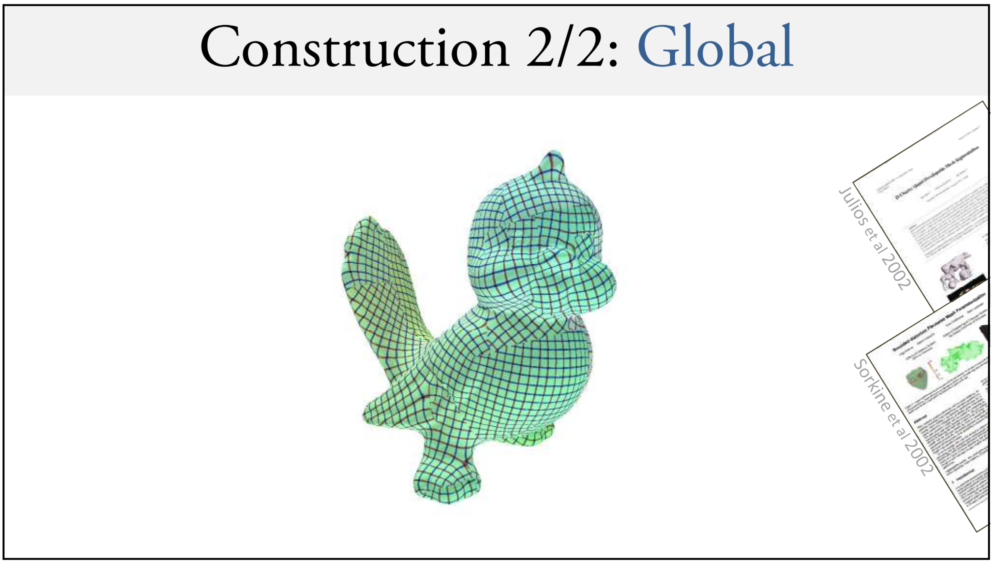
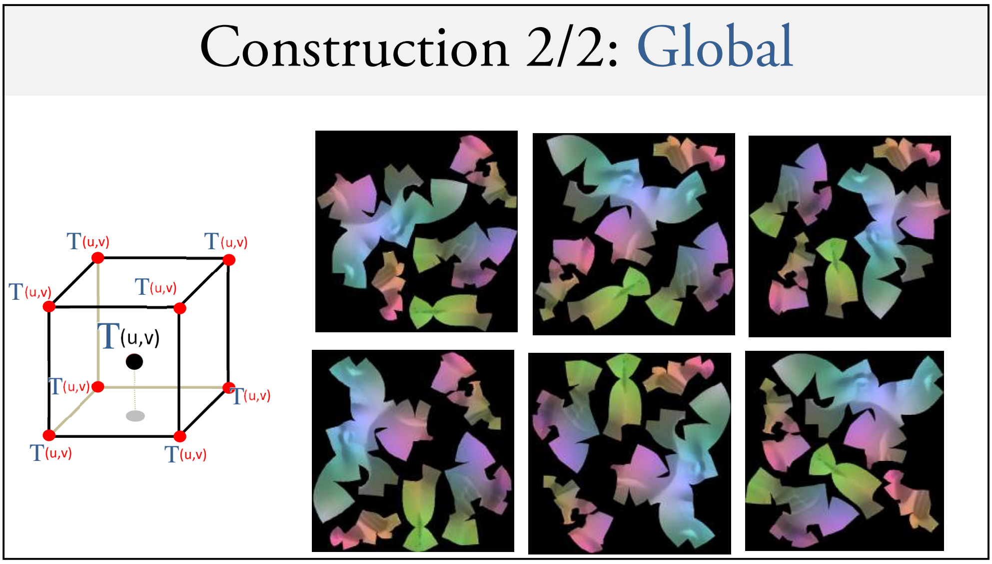
- Good / Few cuts

Near S :

~ constant in normal directions



Construction 2/2: Global



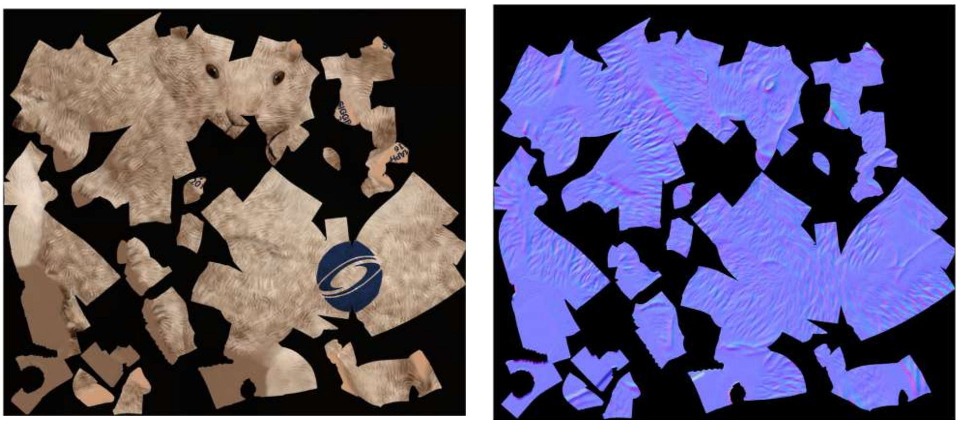
Construction 2/2: Global

Construction 2/2: Global

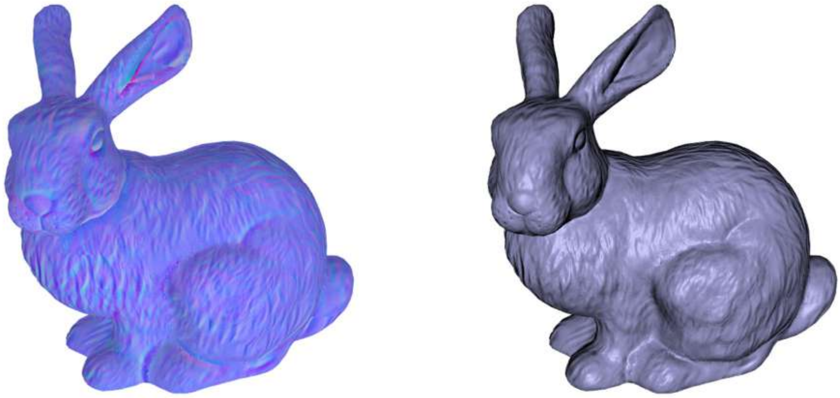
Texture Authoring: business as usual

Texture Authoring: business as usual

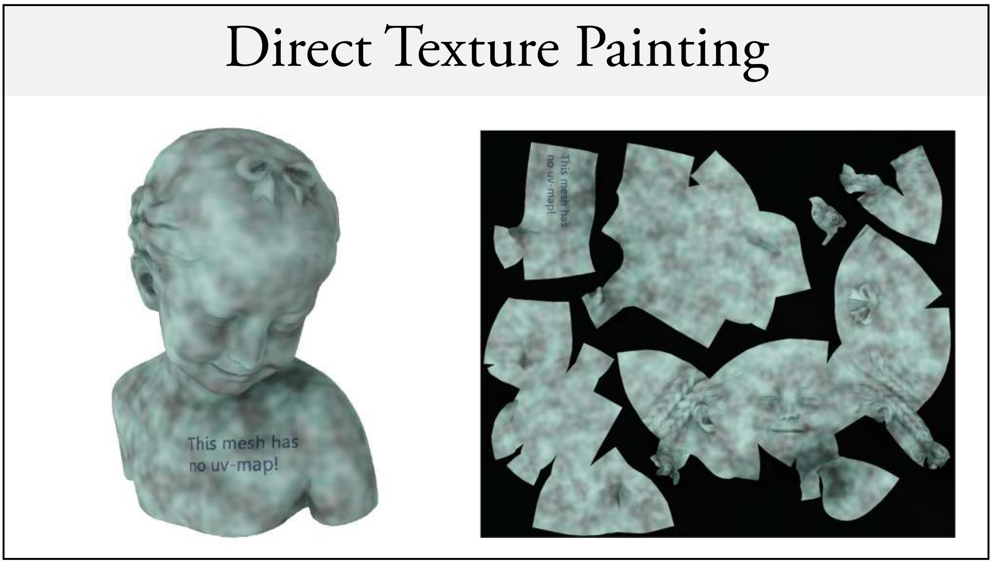
Texture Authoring: business as usual



VeUV with Tangent Space Normal Mapping



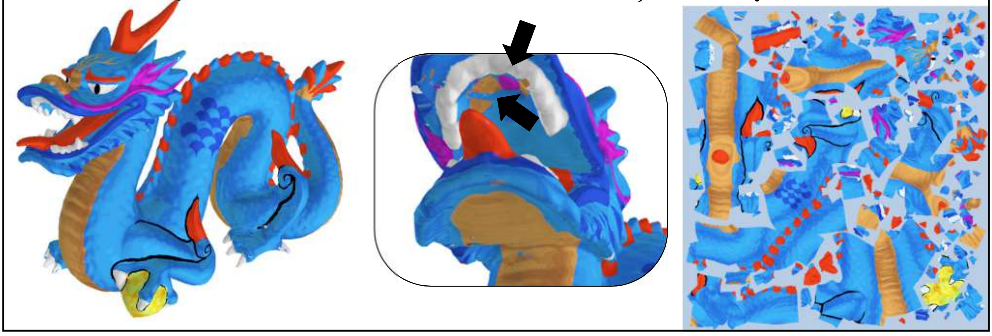
VeUV with Skinning



Direct Texture Painting

Limitation

- Not one solution for all cases
- Too tiny features → local loss of injectivity



Conclusions

A new UV-map representation (volumetric!)

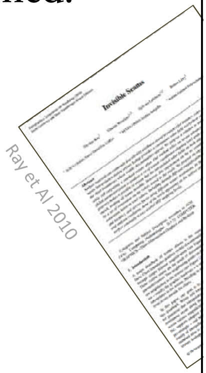
Equivalent to traditional per-vertex one…

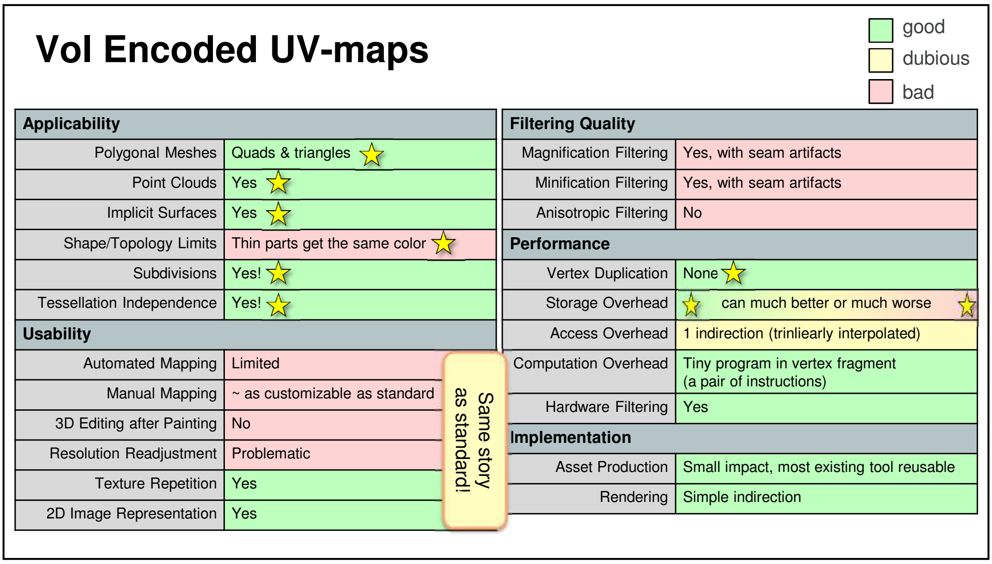
…but :

- applicable to most surface representations (not just 2manifold meshes)
- no vertex replications (in polygonal mesh)
- often << space (but not always)
- independent on the meshing!
- texture + UV-map can be shared by different LoDs

VeUV with Invisible Seams ?

- The two techniques can in theory be combined!


Ray et Al 2010



Vol Encoded UV-maps

🟩 good
🟨 dubious
🟥 bad

Applicability	
Polygonal Meshes	🟩 Quads & triangles ☆
Point Clouds	🟩 Yes ☆
Implicit Surfaces	🟩 Yes ☆
Shape/Topology Limits	🟥 Thin parts get the same color ☆
Subdivisions	🟩 Yes! ☆
Tessellation Independence	🟩 Yes! ☆
Usability	
Automated Mapping	🟥 Limited
Manual Mapping	🟥 ~ as customizable as standard
3D Editing after Painting	🟥 No
Resolution Readjustment	🟥 Problematic
Texture Repetition	🟩 Yes
2D Image Representation	🟩 Yes

Same story as standard!

Filtering Quality	
Magnification Filtering	🟥 Yes, with seam artifacts
Minification Filtering	🟥 Yes, with seam artifacts
Anisotropic Filtering	🟥 No
Performance	
Vertex Duplication	🟩 None ☆
Storage Overhead	🟨 ☆ can much better or much worse ☆
Access Overhead	🟨 1 indirection (trinliearly interpolated)
Computation Overhead	🟩 Tiny program in vertex fragment (a pair of instructions)
Hardware Filtering	🟩 Yes
Implementation	
Asset Production	🟩 Small impact, most existing tool reusable
Rendering	🟩 Simple indirection

REFERENCES

David Benson and Joel Davis. 2002. Octree textures. *ACM Transactions on Graphics* 21, 3 (2002), 785–790.

Brent Burley and Dylan Lacewell. 2008. Ptex: Per-Face Texture Mapping for Production Rendering. In *Eurographics Symp. on Rendering (EGSR'08)*. 1155–1164.

Per H. Christensen and Dana Batali. 2004. An Irradiance Atlas for Global Illumination in Complex Production Scenes. In *Proc. of Rendering Techniques (EGSR'04)*. 133–141.

Cyril Crassin, Fabrice Neyret, Sylvain Lefebvre, and Elmar Eisemann. 2009. GigaVoxels: Ray-guided Streaming for Efficient and Detailed Voxel Rendering. In *Proceedings of Symposium on Interactive 3D Graphics and Games (I3D '09)*. ACM, 15–22.

Carsten Dachsbacher and Sylvain Lefebvre. 2008. *Efficient and Practical TileTrees (in Shader X6)*. Charles River Media. http://www-sop.inria.fr/reves/Basilic/2008/DL08

Mathieu Desbrun, Mark Meyer, and Pierre Alliez. 2002. Intrinsic Parameterizations of Surface Meshes. *Comput. Graph. Forum* 21, 3 (2002), 209–218.

Ismael García, Sylvain Lefebvre, Samuel Hornus, and Anass Lasram. 2011. Coherent parallel hashing. *ACM Trans. Graph.* 30, 6 (2011).

Ying He, Hongyu Wang, Chi-Wing Fu, and Hong Qin. 2009. A divide-and-conquer approach for automatic polycube map construction. *Computers & Graphics* 33, 3 (2009), 369–380.

K. Hormann, B. Lévy, and A. Sheffer. 2007. Mesh parameterization: Theory and practice. *SIGGRAPH Course Notes* (2007).

Martin Kraus and Thomas Ertl. 2002. Adaptive Texture Maps. In *Proceedings of Conference on Graphics Hardware (HWWS '02)*. 7–15.

Thibault Lambert. 2015. From 2D to 3D Painting with Mesh Colors. In *ACM SIGGRAPH 2015 Talks (SIGGRAPH '15)*. ACM, New York, NY, USA, Article 72, 1 pages.

Sylvain Lefebvre and Carsten Dachsbacher. 2007. TileTrees. In *Proceedings of the Symposium on Interactive 3D Graphics and Games*. ACM, 25–31.

Sylvain Lefebvre and Hugues Hoppe. 2006. Perfect spatial hashing. In *ACM Transactions on Graphics*, Vol. 25. ACM, 579–588. Issue 3.

Sylvain Lefebvre, Samuel Hornus, and Fabrice Neyret. 2005. Octree textures on the GPU. *GPU gems* 2 (2005), 595–613.

Julian Panetta, Michael Kazhdan, and Denis Zorin. 2012. *Volumetric Basis Reduction for Global Seamless Parameterization of Meshes*. Technical Report. New York University.

Nico Pietroni, Marco Tarini, Olga Sorkine, and Denis Zorin. 2011. Global parametrization of range image sets. *ACM Trans. Graph.*, Article 149 (2011), 10 pages.

Budirijanto Purnomo, Jonathan D Cohen, and Subodh Kumar. 2004. Seamless texture atlases. In *Proceedings of Symposium on Geometry Processing*. ACM, 65–74.

Nicolas Ray, Vincent Nivoliers, Sylvain Lefebvre, and Bruno Levy. 2010. Invisible Seams. *Computer Graphics Forum* (2010).

Alla Sheffer, Emil Praun, and Kenneth Rose. 2006. Mesh parameterization methods and their applications. *Foundations and Trends® in Computer Graphics and Vision* 2, 2 (2006), 105–171.

Marco Tarini. 2012. Cylindrical and toroidal parameterizations without vertex seams. *Journal of Graphics Tools* 16, 3 (2012), 144–150.

Marco Tarini. 2016. Volume-encoded UV-maps. *ACM Transactions on Graphics* 35, 4, Article 107 (July 2016), 13 pages.

Marco Tarini, Kai Hormann, Paolo Cignoni, and Claudio Montani. 2004. PolyCube-Maps. *ACM Trans. Graph.* 23 (2004), 853–860. Issue 3.

Hongyu Wang, Ying He, Xin Li, Xianfeng Gu, and Hong Qin. 2008. Polycube splines. *Computer-Aided Design* 40, 6 (2008), 721–733.

Jiazhil Xia, Ismael Garcia, Ying He, Shi-Qing Xin, and Gustavo Patow. 2011. Editable polycube map for GPU-based subdivision surfaces. In *Symp. on interactive 3D graphics and games*. ACM, 151–158.

Cem Yuksel. 2016. Mesh Colors with Hardware Texture Filtering. In *ACM SIGGRAPH 2016 Talks (SIGGRAPH '16)*. ACM, New York, NY, USA.

Cem Yuksel, John Keyser, and Donald H. House. 2010. Mesh colors. *ACM Transactions on Grapics* 29, 2, Article 15 (2010), 11 pages.