Lecture 3: Introduction to Point-based Graphics

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Remark

- This lecture is a summary of Siggraph 2004 course on Point-based Computer Graphics:
  - http://graphics.stanford.edu/~mapauly/Pdfs/SigCourse04.pdf

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Overview

- Introduction and motivation
  - The rendering pipeline
  - Representations in graphics revisited
    - Volume, triangle → points
- 3D geometry acquisition
  - 3D scanners technology
- Point-based representation
  - Surface elements: *Surfel*
- Processing and editing
  - (skip)
- Rendering
- Summary

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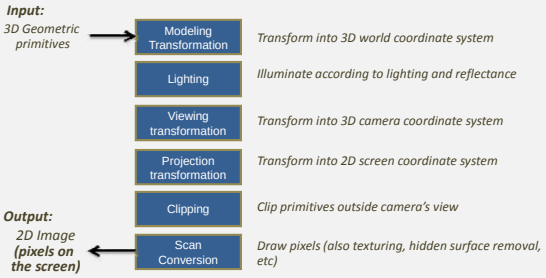
The rendering pipeline

3D Rendering: Conversion of a 3D scene into an image



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The rendering pipeline

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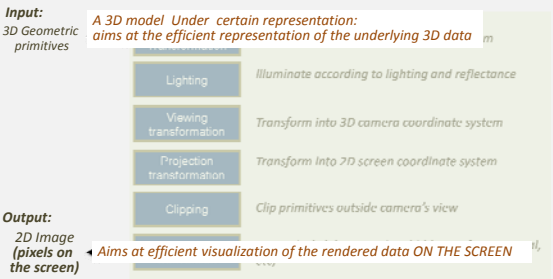

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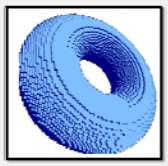
Representation in Graphics

- Volume representation
  - Extension of 2D images into 3D images
  - 3D grid of cells (*voxels*)
    - A voxel stores some properties of the model
  - Suitable when we want to represent interior details:
    - Medical applications,
    - Fluid simulation,
    - Natural phenomena simulation,
    - Etc,..



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Representation in Graphics

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    - Each voxel stores some properties of the model
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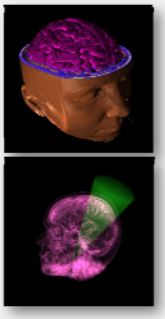

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Representation in Graphics

- Surface representation
  - Represents the boundaries of the 3D object:
    - Parametric (ex. Splines, NURBS)
    - implicit representations
    - Polygon-based representations
    - …. and Point-based representations

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Representation in Graphics

- Parametric and implicit representations
  - Properties
    - ✓Rigorous mathematical concept
    - ✓Robust evaluation of geometric entities
    - ✓Shape control for smooth shapes
    - ✖Require proper parameterization
    - ✖Discontinuity modeling
    - ✖Topological flexibility

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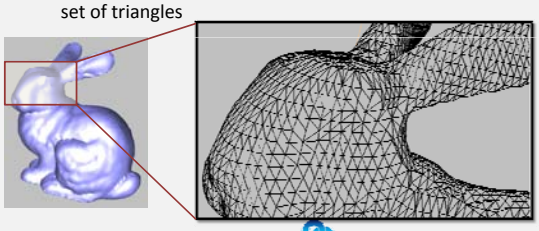
Polygon-based representations

- Functions→ Triangles
  - – Piecewise linear approximations:
    - Given a continuous surface S, it is approximated by a set of triangles



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Polygon-based representations

- Functions→ Triangles
  - – Piecewise linear approximations:
    - Given a continuous surface S, it is approximated by a set of triangles
  - – Irregular sampling of the surface
  - – No parameterization needed (for now)

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Polygon-based representations

- Polynomial → Triangles
  - Properties
    - ✓Simple and efficient representation
    - ✓Hardware pipelines support Δ
    - ✓Advanced geometric processing
    - ✓The widely accepted queen of graphics primitives
    - ✖Sophisticated modeling is difficult
    - ✖(Local) parameterizations still needed
    - ✖Complex LOD management
    - ✖Compression and streaming is highly non-trivial

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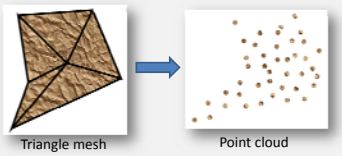
Point-based representation

- Triangles → Points: remove connectivity!!
  - Piecewise linear functions to Delta distributions
    - Discrete samples of geometry
    - No connectivity or topology – most simple
    - Store all attributes per surface sample



Triangle mesh with texture

Point cloud

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Point-based representation

- Triangles → Points: remove connectivity!!
  - Piecewise linear functions to Delta distributions
    - Discrete samples of geometry
    - No connectivity or topology – most simple
    - Store all attributes per surface sample
  - Point clouds
    - Points are natural representations for 3D acquisition systems
  - Meshes constitute an enhancement of point samples

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Motivations (1/2)

- Polygonal complexity
  - Complex models require very large set of polygons
    - Accurate representation requires more than 200,000 polygons
  - Carrying out the connectivity is useless because:
    - Size of polygon << size of a pixel
    - Storage requirement is very expensive

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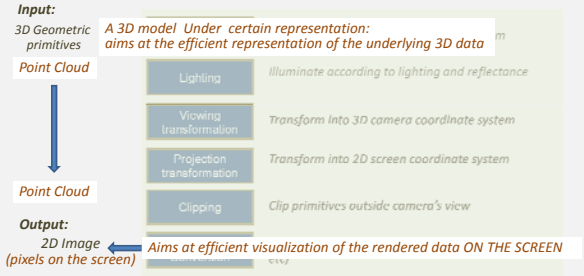
The rendering pipeline revisited

3D Rendering: Conversion of a 3D scene into an image



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Motivations (2/2)

- Upcoming 3D digital photography
  - 3D scanners provide point clouds
    - Generating a consistent triangle mesh is time consuming and difficult
    - Points represent organic models (feathers, trees) much more readily than polygons

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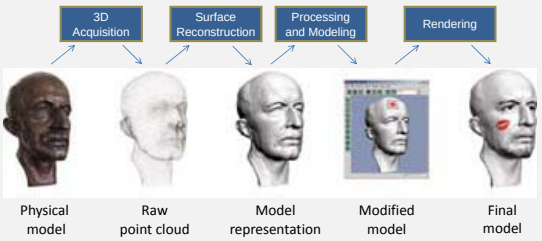
3D Content Creation Pipeline



Points as a generalization of pixels !!

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Acquisition of geometry and appearance

- How can we capture reality ?
  - Real objects have complex geometry
    - feather, bonsai trees, ...
  - Appearance in arbitrary environments with arbitrary lighting
    - rendering a glass of beer in a complex surroundings
    - Specular, fuzzy, and transparent materials are very difficult to scan.

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Acquisition of geometry and appearance

- Goals
  - Fully-automated 3D model creations
    - (or minimum user input)
  - Faithful acquisition and representation of appearance
    - Good geometry is always needed
    - Faithful reproduction of the appearance.
  - Placement into new virtual environments

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3D geometry acquisition

- Contact digitizers
  - Direct physical contact with the object to scan
  - Lot of manual labor
- Passive methods (using cameras)
  - Requires that the object has texture
  - Requires that the BRDF of the objects is Lambertian
- Active light imaging systems
  - Use active laser range scanners
  - Very accurate
  - Severe restrictions on the types of materials
    - Ex.: specular and fuzzy materials are difficult.

4 millions points [Levoy et al. 2000]

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Stereo-vision for 3D acquisition

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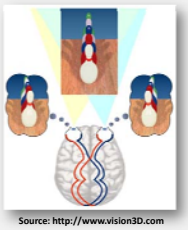
Binocular vision

- Why humans have two eyes ?
  - Because of our binocular vision we can
    - See **WHERE** objects are in relation to our own bodies with much greater precision,
    - See a little bit **AROUND** solid objects without moving our heads,
    - Perceive and measure **EMPTY** space around us.



Source: http://www.vision3D.com

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Binocular Vision Blessings

- If You've Got Stereo Vision, Count Your Blessings!
  - The American Academy of Ophthalmology, Sept., 1996:
    - "many occupations are not open to people who have good vision in one eye only [*i.e. people without stereo vision*]"
  - Few examples of occupations that depend heavily on stereo vision:
    - Baseball player
    - Waitress, Driver
    - Architect, Surgeon, Dentist
  - Few examples of general actions that depend heavily on stereo vision:
    - Throwing, catching or hitting a ball
    - Driving and parking a car
    - Planning and building a three-dimensional object
    - Threading a needle and sewing
    - Reaching out to shake someone's hand
    - Pouring into a container

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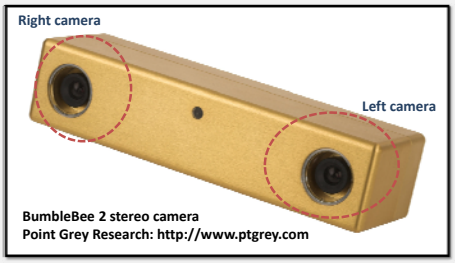
Stereo Vision

- Example of stereo cameras



BumbleBee 2 stereo camera
Point Grey Research: http://www.ptgrey.com

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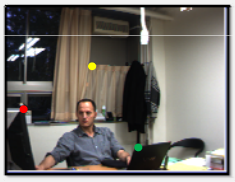
Finding the 3D position

- 3D reconstruction *(inverse imaging process)*
  - Given a point in the 2D image, what are its 3D coordinates in the 3D space



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Finding the 3D position

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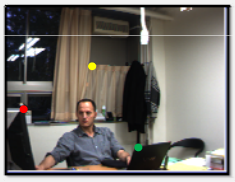

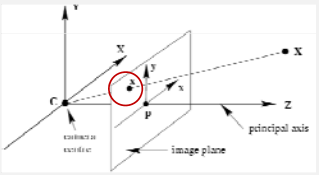

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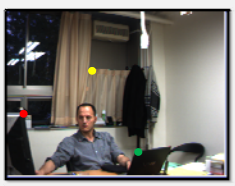

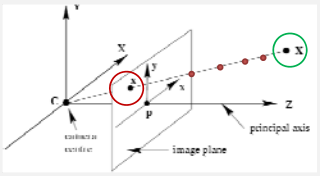

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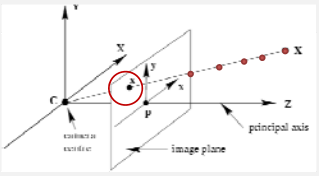
Finding the 3D position

- 3D reconstruction *(inverse imaging process)*
  - Given a point in the 2D image, what are its 3D coordinates in the 3D space

$$\begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} = \frac{1}{C} \begin{bmatrix} * & * & * & * \\ * & * & * & * \\ * & * & * & * \end{bmatrix}^{-1} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

P^{-1}: inverse of 3 X 4 matrix !!!!!



The projection ambiguity

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Finding the 3D position

- Incorporate other cues to resolve the projection ambiguity:
  - A priori knowledge, high-level semantic knowledge
- For humans
  - Monocular cues
    - Relative size between objects
    - Familiar sizes
    - Motion parallax, vanishing points, etc…
  - Eye movements
  - Binocular cues
    - **Stereo-vision:** this is the most developed for normal people
    - **3D Shape from silhouettes**

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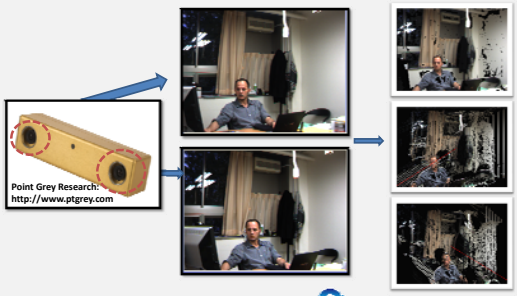
Example of stereo camera



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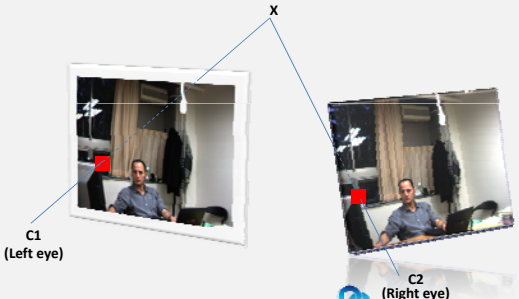
Stereo vision: how does it work

- A flavor of Projective Geometry



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Stereo vision: how does it work

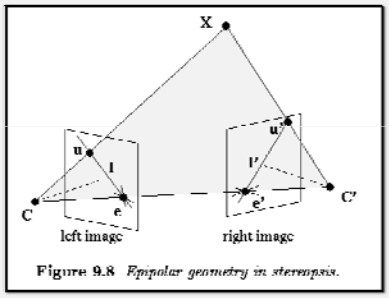

Figure 9.8 *Epipolar geometry in stereopsis.*

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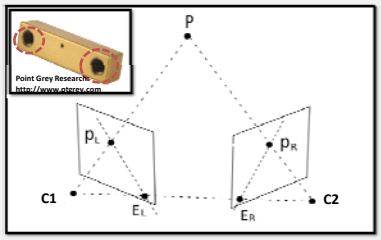
Stereo vision: towards 3D perception

- Simplified case:
  - C1 and C2 are horizontal (the case of BumbleBee 2)



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Geometry of a stereo camera

- Three main targets:
  - **Scene geometry (3D reconstruction)**
    - Given:
      - a set of corresponding points $\{x_i \leftrightarrow x_i'\}$,
      - the cameras P and P'?
    - Can we find the 3D point X ?
  - The answer is YES
    - The stereo-camera allows to compute the depth of each point in the image
      - [DEMO WITH BUMBLEBEE@2]

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Geometry of a stereo camera

- Properties
  - The state of the art of stereo methods generate noisy depth maps
  - It works better on low resolution images (320x240)
  - Many other parameters to tune

  [Illustrate these on the BumbleBee demo]

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Multiple view geometry

- Why not using more than two cameras!!

BumbleBee XB3 ,
Digiclops stereo cameras
Point Grey Research: http://www.ptgrey.com

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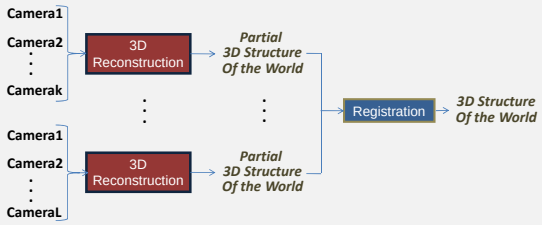
Multiple view geometry

- Networking multiple camera systems



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Multiple view geometry

- Networking multiple camera systems
  - Cover a wide area
  - Deal with occlusions
  - Accurate 3D reconstruction
  - Application to video surveillance

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3D Shape from silhouette

- Stereo vision is not the only way for building the 3D structure of the world.
- [SHOW A VIDEO]

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Appearance acquisition

- BRDF estimation, inverse rendering
  - Fit parametric BRDF model to the observed measurements
    - BRDF models are not capable to represent complex materials (feathers, hair, clothes, etc)
    - Cannot capture inter-reflections, self-shadowing and subsurface scattering
- Image-based modeling + Point-based rendering
  - Images represent objects regardless the complexity of its geometry and appearance
  - Cost to pay:
    - Need of more data

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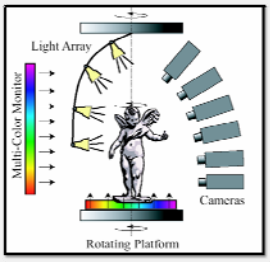
Example of acquisition system



[matsushik et al. 2002] ***Image-based 3D photography using opacity hulls***, in SIGGRAPH 2002

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Example of acquisition system

- General idea
  - Take multiple pictures of the object from multiple views
- System architecture
  - Objects place onto a plasma display, mounted on a rotating platform
  - Array of lights mounted on a rotating overhead platform
  - Six video cameras on a stationary arc, pointed toward the object
  - Plasma displays:
    - For multi-background matting techniques to acquire alpha mattes of the object from multiple viewpoints
    - Estimate light transport through transparent and reflective objects
    - They are switched off after the alpha matte acquisition

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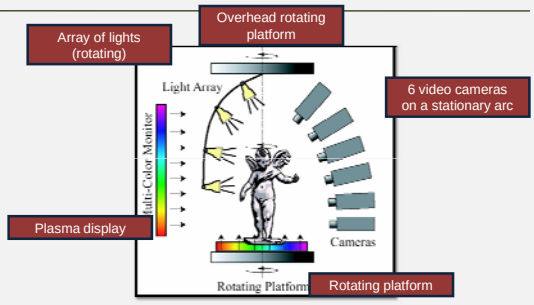
System overview



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Example of acquisition system

- Output of the system
  - Point cloud approximating the geometry of the shape
  - Opacity lightfield at each surface point
    - Think of RGBA values
    - It captures reflections and transparency
  - In general case:
    - Each surface point carries some properties, simplest case is when the point is carrying just its color.

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Example of results

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Example of acquisition system

- Many steps are required in this system
  - Acquisition (we already talked a little bit)
  - Model
  - → Point-based rendering
  - Relighting
  - Reflectance field estimation

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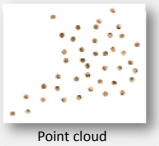
Points as rendering primitives

- Point clouds instead of triangle meshes
  - Introduced in 1985 by [Levoy and Whited 1985]
  - Analogy in 2D:
    - 2D vector graphics vs. pixel graphics

Triangle mesh with texture



Point cloud

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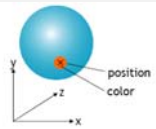
Surface elements - Surfels

- Each point corresponds to a surface element, or ***surfel***, describing the surface in small neighborhood
- Basic surfels:
  - A point with position and a constant color

```
BasicSurfel {
  position;
  color;
}
```



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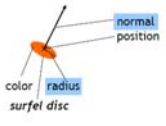
Surface elements - Surfels

- In general
  - Surfels can be extended to store additional attributes
  - The union of surfel discs covers the object such that there are no holes on the surface

```
ExtendedSurfel {
  position;
  color;
  normal;
  radius;
  etc...
}
```



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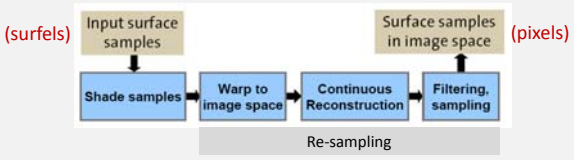
Point rendering pipeline



- Simple, pure forward mapping pipeline
- Surfels carry all information through the pipeline

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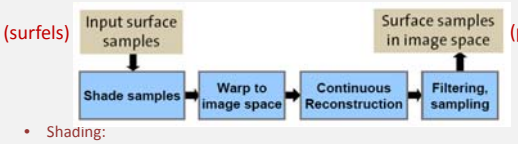
Point rendering pipeline



- Shading:
  - Input surface samples are shaded according to the measured RGBA values
- Projection (warping)
  - Points are projected onto the image space.
- Continuous surface reconstruction
  - A continuous surface is reconstructed in the image space (similar to triangle rasterization)
- Filtering / sampling
  - Filtering and sampling the continuous representation at the output pixel positions (similar to texture filtering and sampling)

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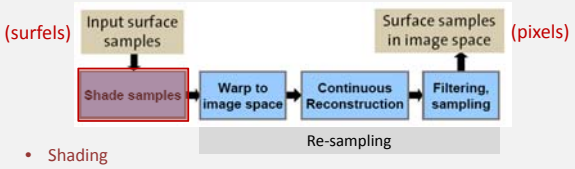
Point rendering pipeline



- Shading
  - The scanner acquires points and colors from different (pre-set) viewing points
  - We want to assign a color to point when rendered from a NEW view point:
    - Blend colors based on the angle between new viewpoint and acquired RGBA images
    - Linear combination of colors from closest views

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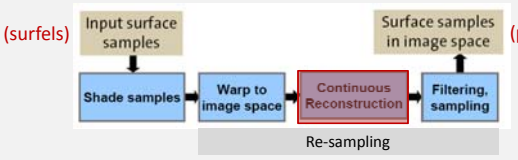
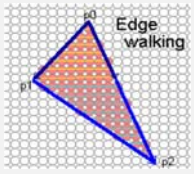
Point rendering pipeline



- Continuous reconstruction
  - Similar to triangle rasterization.
  - We want to do similar thing for surfels when projected to the image domain.



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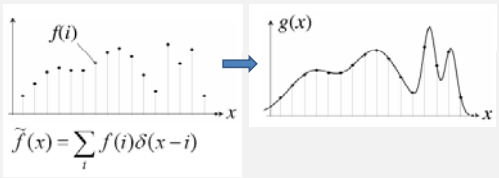
Reconstruction

- Goal
  - Estimate surface properties at unknown locations



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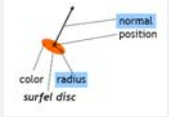
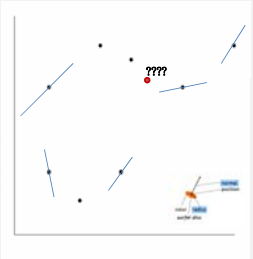
Reconstruction

- Step 1
  - Define local coordinate frame at each point
    - defined by the normal vector
  - Define a reconstruction kernel associated with each point in the local coord. frame:
    - Usually a Gaussian Kernel





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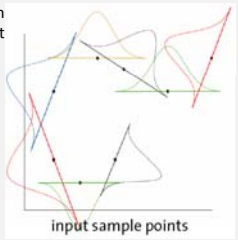
Reconstruction

- Step 3
  - Mapping into a global parameter domain
    - For each reference frame we defin a parameter mapping that convert local coordinates to coordinates in the global parameter domain



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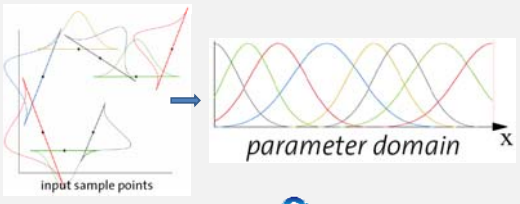
Reconstruction

- Step 3
  - Mapping into a global parameter domain
    - For each reference frame we define a parameter mapping that converts local coordinates to coordinates in the global parameter domain



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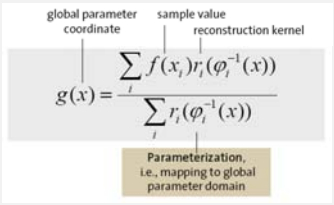
Reconstruction

- Step 4
  - Evaluate the reconstruction equation to reconstruct the surface



- Phi is the mapping from local coord frame to global coord frame.

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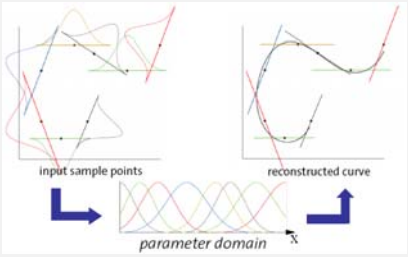
Reconstruction

- Step 4
  - Evaluate the reconstruction equation to reconstruct the surface



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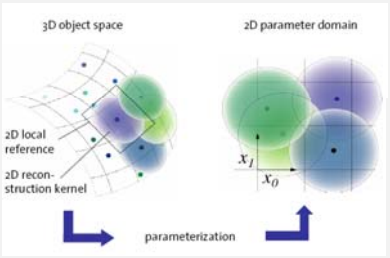
Reconstruction

- Step 4
  - In 3D



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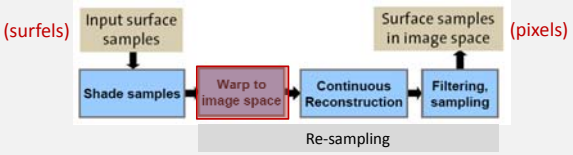
Point rendering pipeline



- Projection / warp
  - Exactly the same as polygon representation

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Warping

- Steps:
  - Use image space as global parameter domain
  - Warp local reference domains to image space using 2D to 2D projective mapping
  - Compute weighted sum of reconstruction kernels in image space

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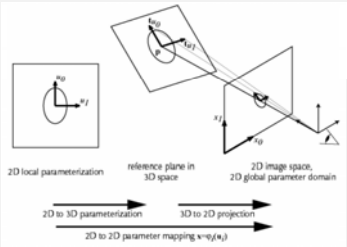
Warping

The pose of the tangent plane and its perspective projection determine the 2D-2D mapping



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Warping

- Reconstruction kernels in image space are called *footprints* or *splats*

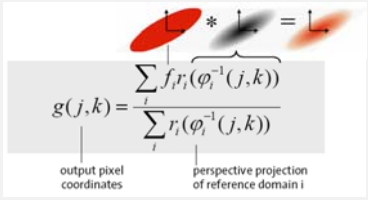

Illustration of the reconstruction of the color of a point

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Splatting algorithm

- The rendering algorithm is called *splatting algorithm*

```
for each sample point {
  shade surface sample;
  splat = projected reconstruction
  kernel;
  rasterize and accumulate splat;
}
for each output pixel {
  normalize;
}
```


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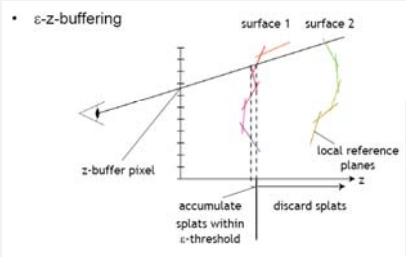
Splatting algorithm

- Visibility: *Hidden surface removal*



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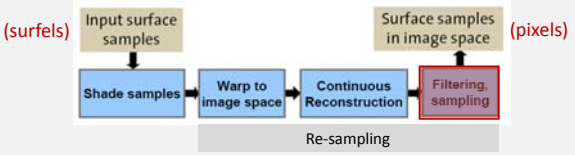
Point rendering pipeline



- Filtering / resampling
  - Sample the reconstructed signal at the output pixel locations:
    - Apply some filtering to the reconstructed signal before sampling it (to achieve high image quality)

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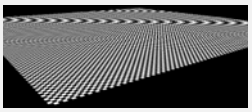
Filtering / resampling

- Antialiasing
  - Rendering using warped reconstruction kernels does not prevent aliasing artifacts:



Moire patterns on highly structured patterns

Disintegration of textures with Highly fine details

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Filtering / resampling

- Antialiasing
  - Rendering using warped reconstruction kernels does not prevent aliasing artifacts:
    - Aliasing occurs when sampling a signal that is not band-limited to the Nyquist frequency of the sampling grid
    - Aliasing is avoided by pre-filtering, i.e., band-limiting to the Nyquist frequency before sampling
  - To avoid aliasing artifacts:
    - Re-sampling with pre-filtering

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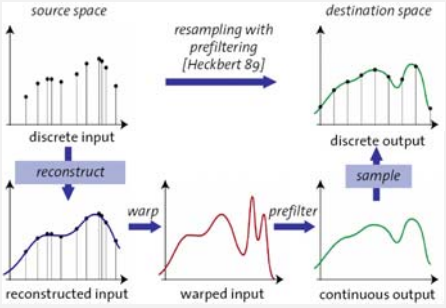
Resampling with pre-filtering



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Rendering results

Head 429,075 points | Helicopter 987,552 points | Mattern horn 4,782,011 points

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Performance

- Software implementation [Zwicker et al. 2001]
  - 1.1 GHz AMD Athlon, 1.5 Gbyte RAM

Data	#Points	256 x 256	512 x 512
Scanned head	429'075	1.3 fps	0.7 fps
Helicopter	987'552	0.6 fps	0.3 fps
Matterhorn	4'782'011	0.2 fps	0.1 fps

Scanned head | Helicopter | Matterhorn

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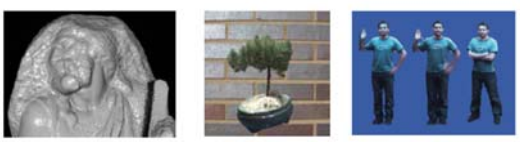
Applications of point rendering

- Direct visualization of point clouds from 3D scanners [Rusinkiewicz et al. 2000, Matusik et al. 2002, Xu et al. 2004]
- Real-time 3D reconstruction and rendering for virtual reality applications [Gross et al. 2003]



[Rusinkiewicz et al. 2000] [Matusik et al. 2002] [Gross et al. 2003]

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Applications of point rendering

- Hybrid point and polygon rendering systems [Chen et al. 2001, Cohen et al. 2001]
- Rendering animated scenes [Wand et al. 2002]

[Chen et al. 2001] [Wand et al. 2002]

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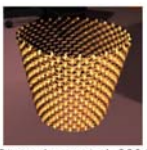
Applications of point rendering

- Interactive display of huge meshes [Wand et al. 2001, Deussen et al. 2002]
- On the fly sampling and rendering of procedural objects [Stamminger et al. 2001]
- Modeling and editing [Zwicker et al. 2002, Pauly et al. 2003]


[Deussen et al. 2002]


[Stamminger et al. 2001]


[Pauly et al. 2003]

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Conclusions Summary

- Point rendering as a re-sampling process
  - High quality point splatting with antialiasing using a pre-filtering approach
- Performance
  - 3 million high quality splats per second with hardware support [Zwicker et al. 2004]
  - 1 million points per second in software
- Various applications for point splatting have been explored

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Future work

Interesting directions to explore

- Rendering hardware
  - Dedicated point rendering hardware
- Extension of current hardware

- Unifying rendering primitives for all sorts of surface representations
  - Rendering architecture for on the fly sampling and rendering

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Resources

- Online resources:
  - Point-based graphics resource: http://hksmyweb.hinet.net/Resource/PointBasedPaper.html
- Online courses:
  - Siggraph 2004 course: http://graphics.stanford.edu/~mapauly/publications
- Software
  - PointShop3D: (Computer Graphics Lab at ETH Zurich) http://www.pointshop3d.com
  - Qsplat (Computer Graphics Lab at Stanford) http://graphics.stanford.edu/software/qsplat/

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Don't forget

- Lecture's slides:
  - Check my homepage to download the latest version of the lecture slides:
    - http://www.img.cs.titech.ac.jp/~hamid/courses/

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Questions

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