Computer Graphics

- Texturing Methods -

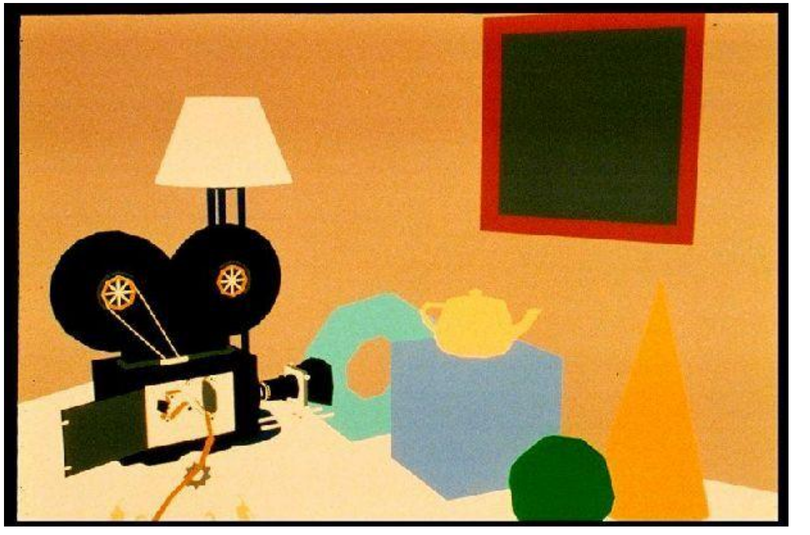
Overview

- **Last time**
  - BRDFs
  - Shading
- **Today**
  - Texturing
    - Texture parameterization
  - Procedural methods
    - Procedural textures
    - Fractal landscapes
- **Next lecture**
  - Texture filtering
  - Alias & signal processing

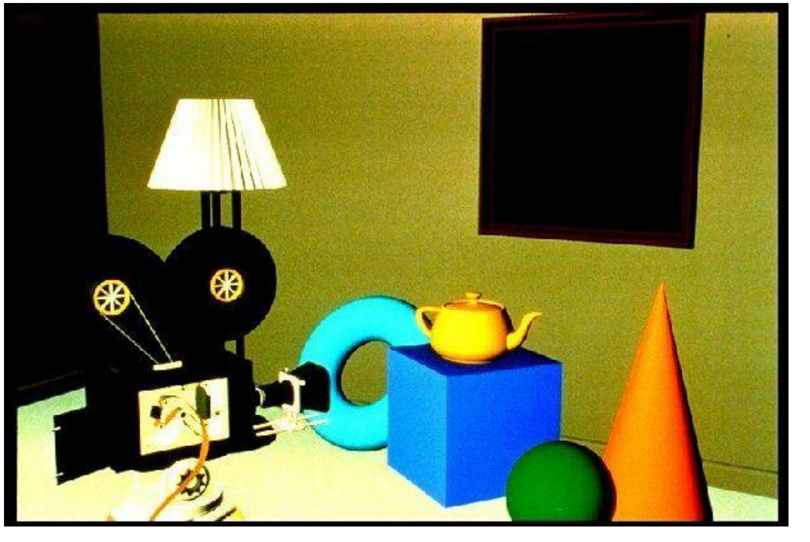
TEXTURING

Simple Illumination

- **No illumination**
- **Constant colors**

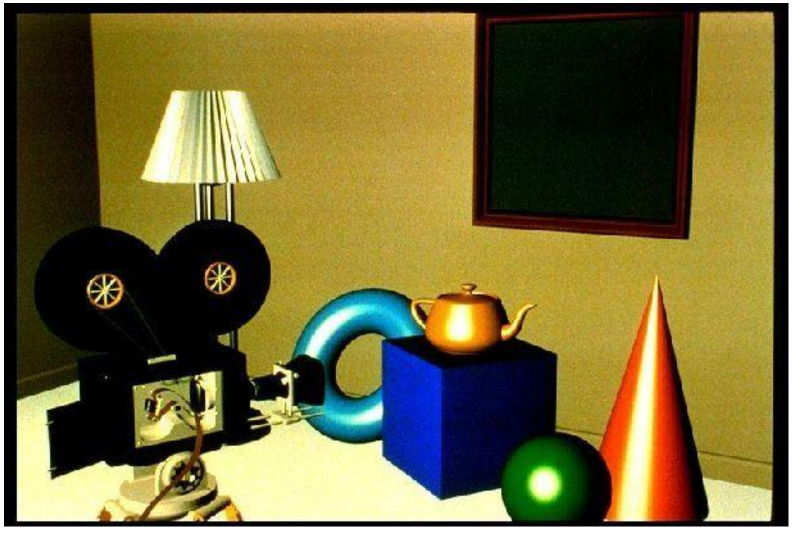


- **Parallel light**
- **Diffuse reflection**



Standard Illumination

- **Parallel light**
- **Specular reflection**

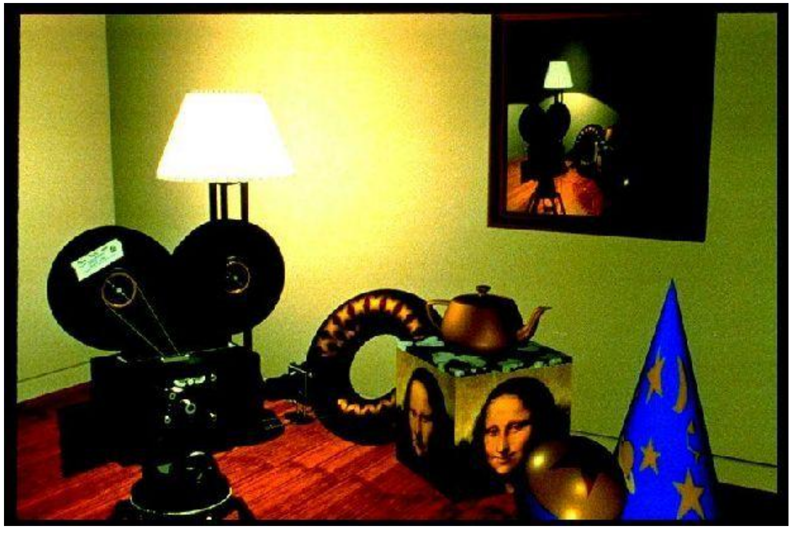


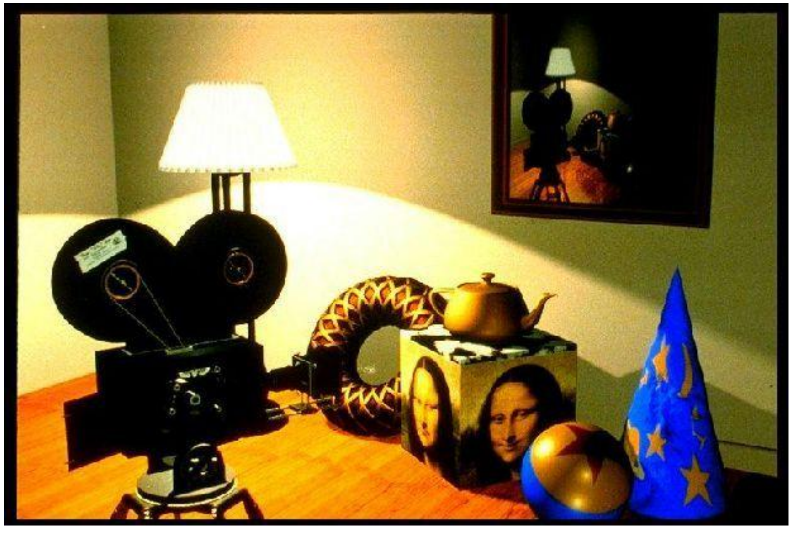
- **Multiple local light sources**
- **Different BRDFs**

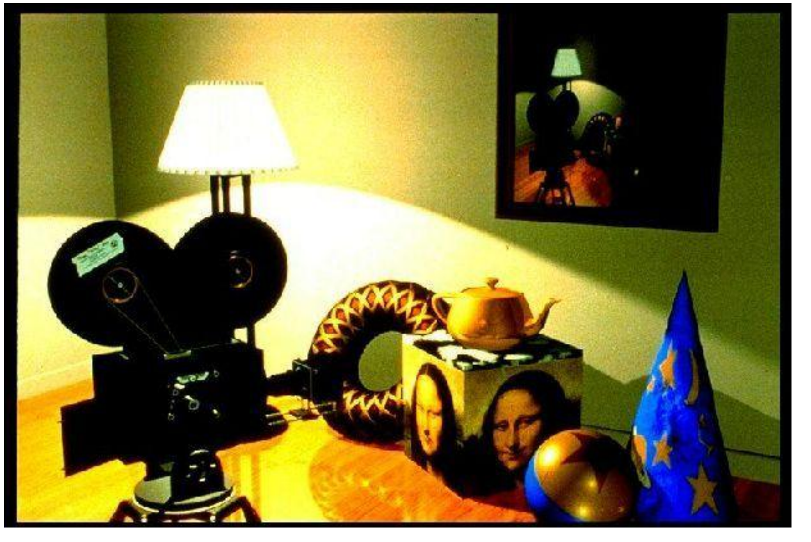
- **Object properties constant over surface**

Texturing

- **Varying object properties**
  - 2D image reflectance textures
  - Bump-mapping
- **Environment characteristics**
  - Shadows
  - Reflection textures



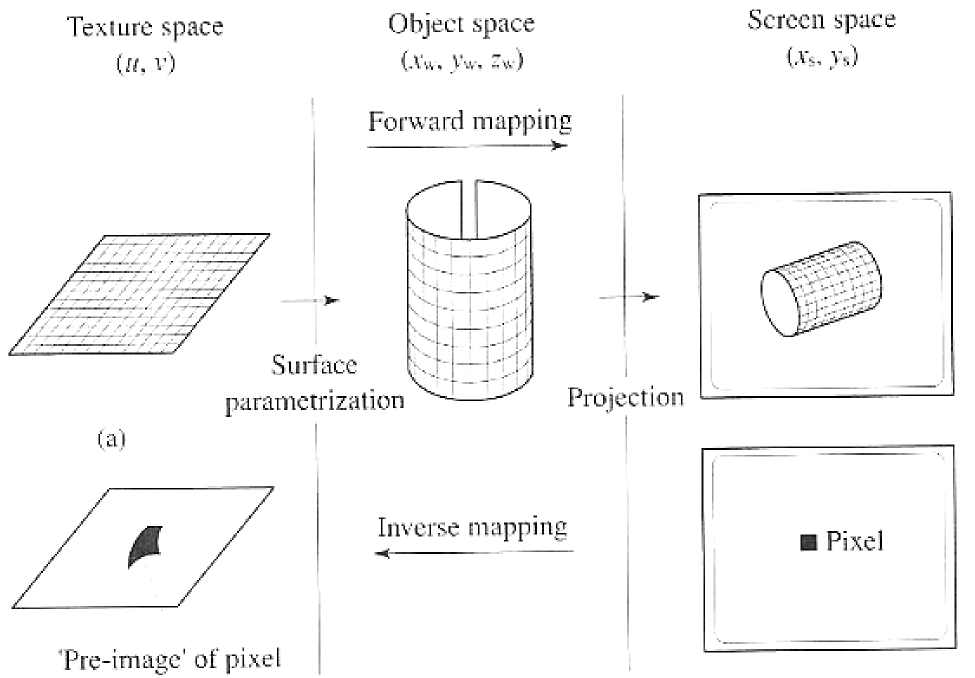




Texture-Modulated Quantities

- **Modulation of object surface properties**
- **Reflectance**
  - Diffuse reflection coefficient k_d
  - Specular reflection coefficient k_s
- **Opacity (α)**
  - Modulating transparency (e.g. for fences)
- **Normal vector**
  - Bump mapping: $N'(P) = N(P + t\,N)$ (in normal direction, height)
  - Normal mapping: $N' = N + \Delta N$ (arbitrary offset)
- **Geometry**
  - Displacement mapping: $P' = P + \Delta P$
- **Distant illumination**
  - Environment mapping / reflection mapping

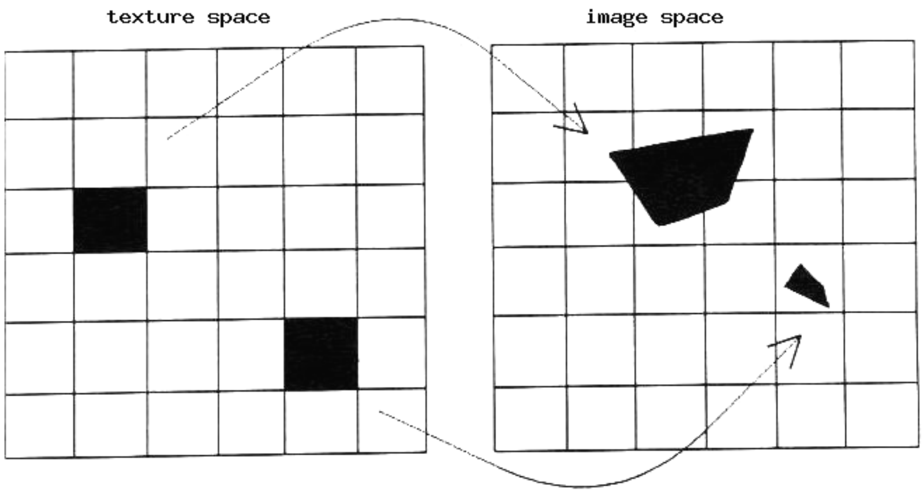
2D Texture Mapping



- **Forward mapping**
  - Object surface parameterization
  - Projective transformation
- **Inverse mapping**
  - Find corresponding pre-image/footprint of each pixel in texture
  - Integrate over pre-image

Forward Mapping

- **Maps each texel to its position in the image**
- **Uniform sampling of texture space does not guarantee uniform sampling in screen space**
  - Can create holes, need to scan-convert (see later)
- **Possibly used if**
  - The texture-to-screen mapping is difficult to invert
  - The texture image does not fit into memory
    - Process texture in tiles in order
    - Texture scanning:
    - for v
    - for u
    - compute x(u,v) and y(u,v)
    - copy TEX[u,v] to SCR[x,y]

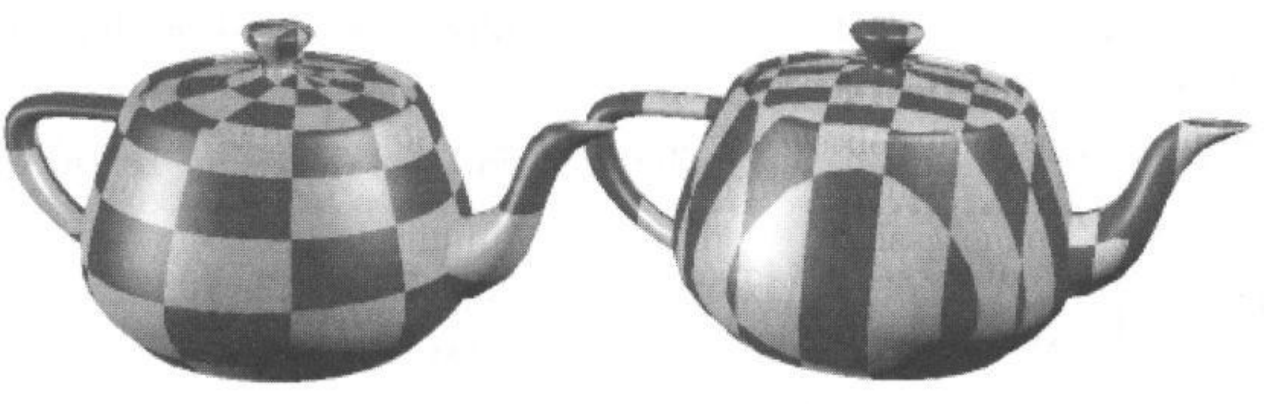


Surface Parameterization

- **To apply textures we need 2D coordinates on surfaces**

  → Parameterization

- **Some objects have a natural parameterization**
  - Sphere: spherical coordinates $(\varphi, \theta) = (2\pi\, u, \pi\, v)$
  - Cylinder: cylindrical coordinates $(\varphi, h) = (2\, \pi\, u, H\, v)$
  - Parametric surfaces (such as B-spline or Bezier surfaces → later)
- **Parameterization is less obvious for**
  - Polygons, implicit surfaces, teapots…



Triangle Parameterization

- **Triangle is a planar object**
  - Has implicit parameterization (e.g. barycentric coordinates)
  - But we need more control: placement of triangle in texture space
- **Assign texture coordinates *(u,v)* to each vertex (x_o,y_o,z_o)**
- **Apply viewing projection $(x_o,y_o,z_o) \rightarrow (x,y)$ (details later)**
- **Yields full texture transformation (warping) *(u,v)* → *(x,y)***

$$\boxed{x = \frac{au + bv + c}{gu + hv + i} \qquad y = \frac{du + ev + f}{gu + hv + i}}$$

  - In homogeneous coordinates (by embedding (u,v) as (u,v,1))

$$\begin{bmatrix} x' \\ y' \\ w \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} \begin{bmatrix} u' \\ v' \\ q \end{bmatrix}; (x,y) = \left(\frac{x'}{w}, \frac{y'}{w}\right), (u,v) = \left(\frac{u'}{q}, \frac{v'}{q}\right)$$

  - Transformation coefficients determined by 3 pairs *(u,v)→(x,y)*
    - Three linear equations
    - Invertible iff neither set of points is collinear

Triangle Parameterization (2)

- **Given** $$\begin{bmatrix} x' \\ y' \\ w \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} \begin{bmatrix} u' \\ v' \\ q \end{bmatrix}$$
- **The inverse transform *(x,y)*→*(u,v)* is**

$$\begin{bmatrix} u' \\ v' \\ q \end{bmatrix} = \begin{bmatrix} ei - fh & ch - bi & bf - ce \\ fg - di & ai - cg & cd - af \\ dh - eg & bg - ah & ae - bd \end{bmatrix} \begin{bmatrix} x' \\ y' \\ w \end{bmatrix}$$

- **Coefficients must be calculated for each triangle**
  - Rasterization
    - Incremental bilinear update of *(u',v',q)* in screen space
    - Using the partial derivatives of the linear function (i.e. constants)
  - Ray tracing
    - Evaluated at every intersection
- **Often derivatives are needed as well**
  - Explicitly given in matrix

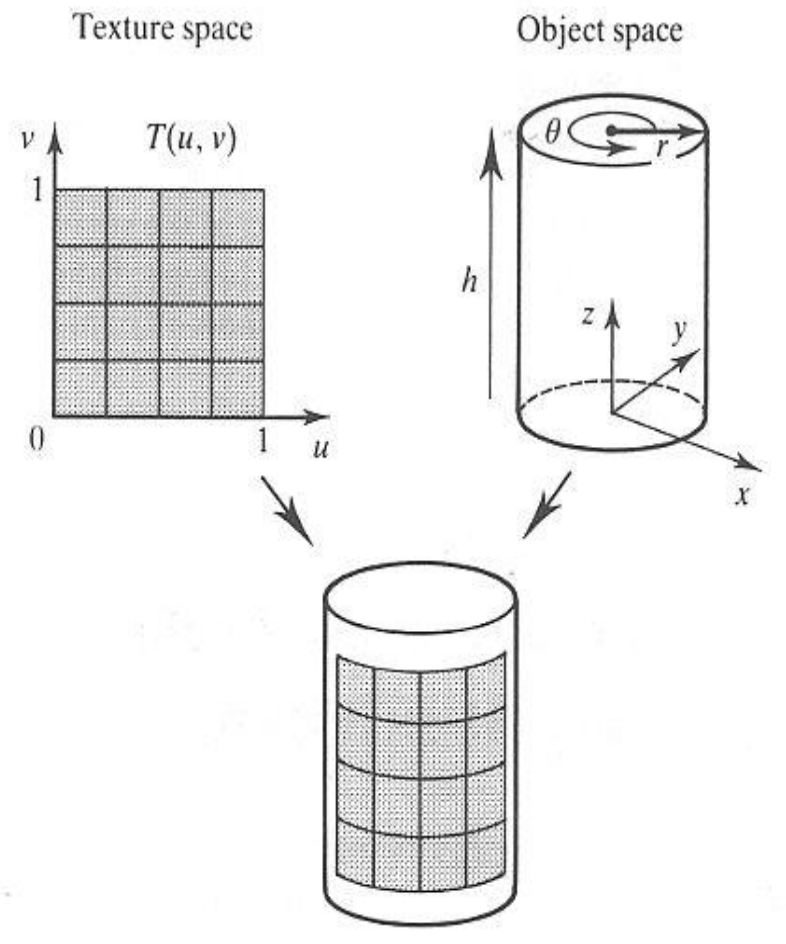
Cylinder Parameterization

- **Transformation from texture space to the cylinder parametric representation can be written as:**

$$(\theta, h) = (2\pi u, vH)$$

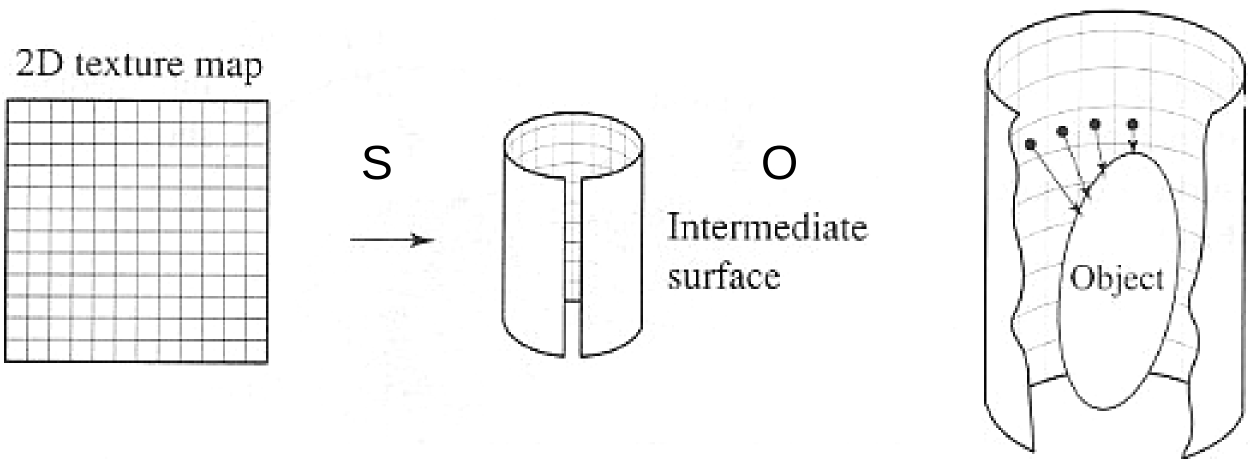
- **where *H* is the height of the cylinder.**
- **The surface coordinates in the Cartesian reference frame can be uniquely expressed as:**

$$x_o = r\cos\theta$$
$$y_o = r\sin\theta$$
$$z_o = h$$



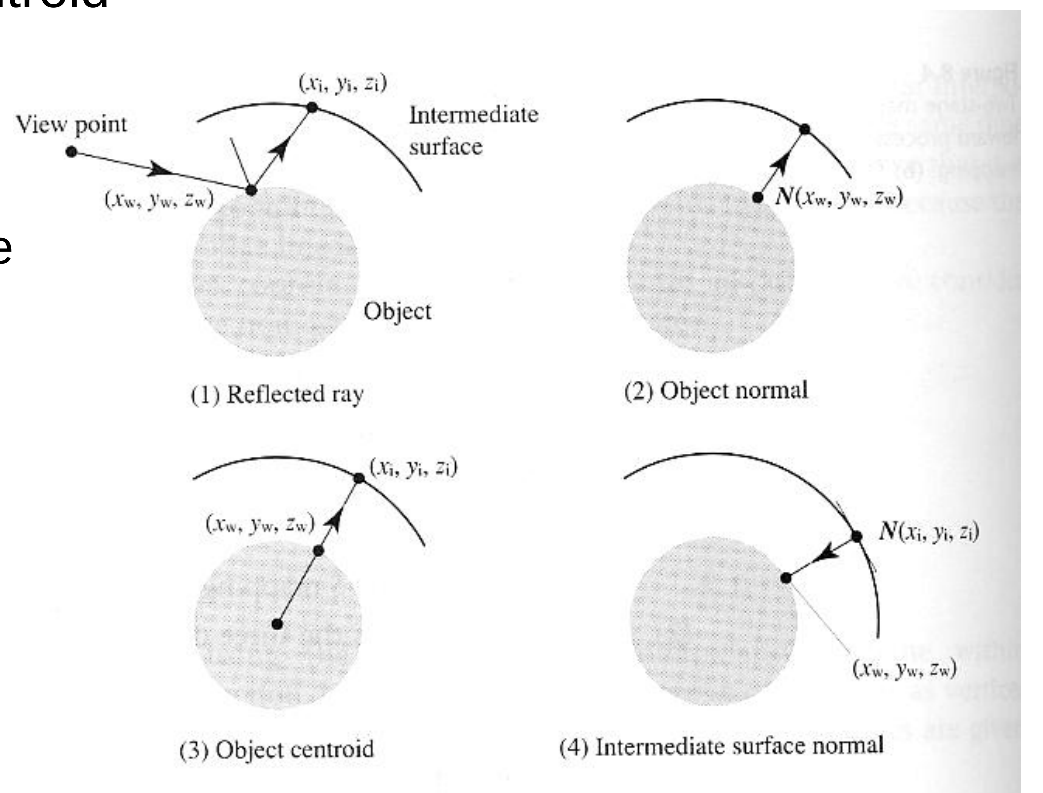
Two-Stage Mapping

- **Inverse mapping for arbitrary 3D surfaces too complex**
- **Approximation technique is used:**
  - Mapping from 2D texture space to a simple 3D intermediate surface (S mapping)
    - Should be a reasonable approximation of the destination surface
    - E.g.: plane, cylinder, sphere, cube, ...
- **Mapping from the intermediate surface to the destination object surface (O mapping)**



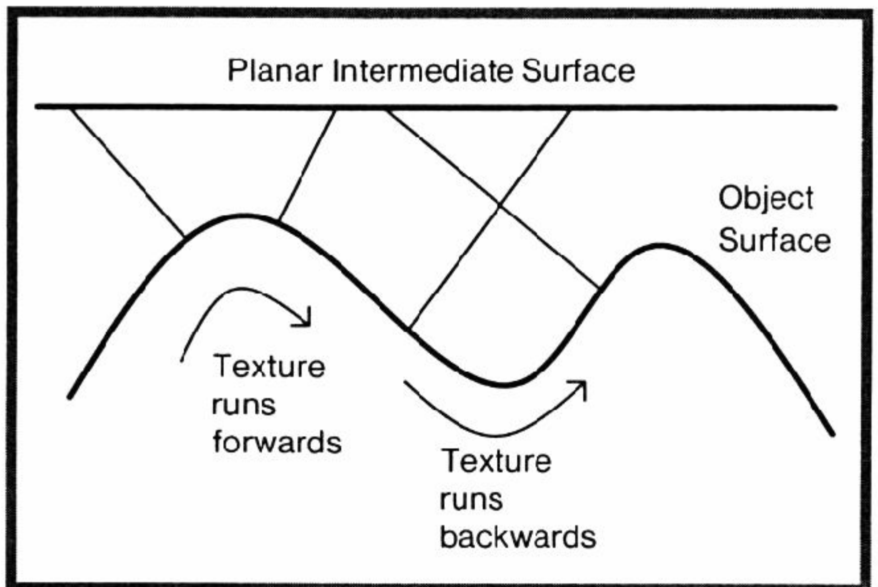
O-Mapping

- **Determine point on intermediate surface through**
  - Reflected view ray
    - Reflection or environment mapping
  - Normal mapping
  - Line through object centroid
  - Shrink-wrapping
    - Forward mapping
    - Normal mapping from intermediate surface



Two-Stage Mapping: Problems

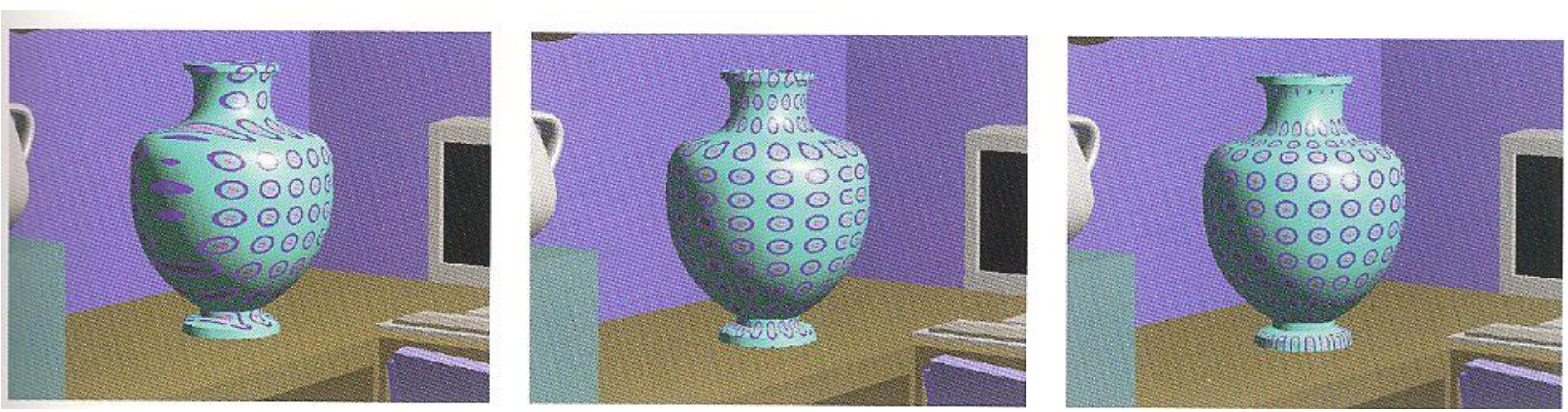
- **May introduce undesired texture distortions if the intermediate surface differs too much from the destination surface**
- **Still often used in practice because of its simplicity**



Surface concavities can cause the texture pattern to reverse if the object normal mapping is used.

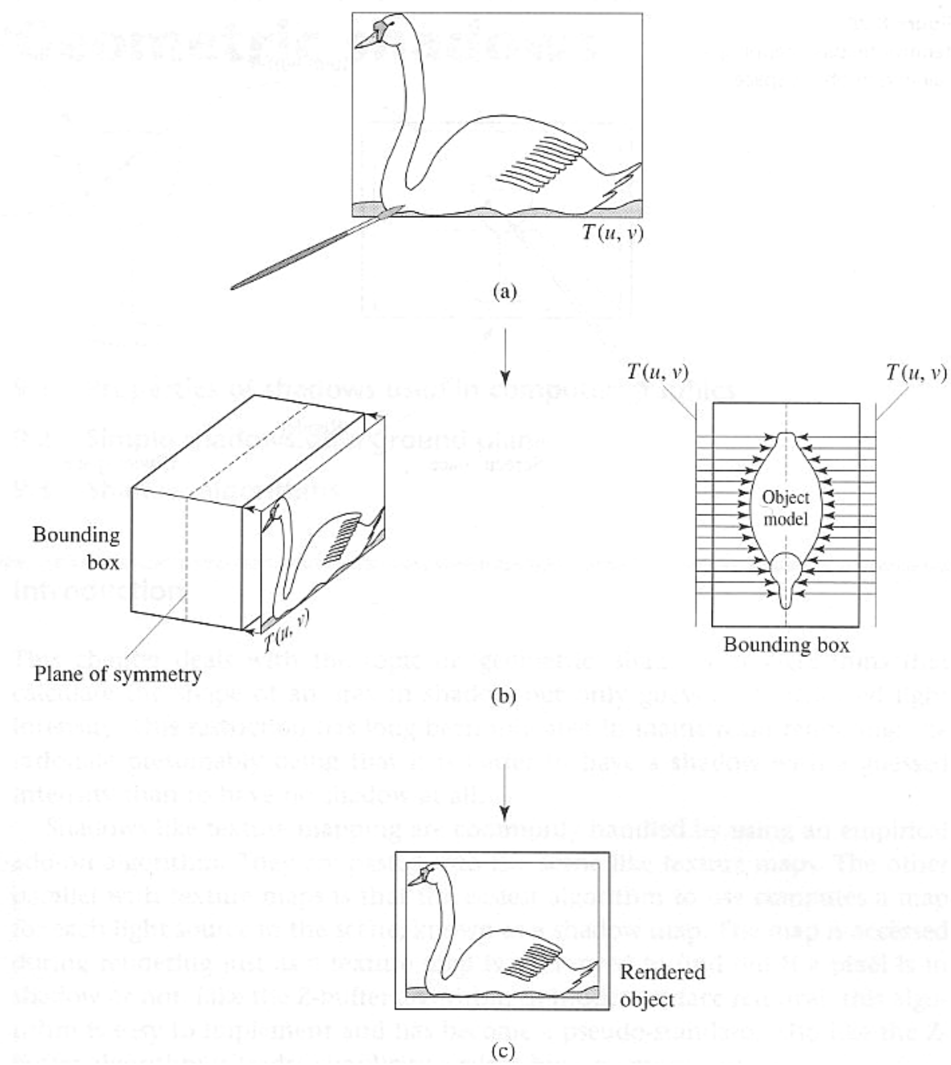
Two-Stage Mapping: Example

- **Different intermediate surfaces**
- **Plane**
  - Strong distortion where object surface normal ⊥ to plane normal
- **Cylinder**
  - Reasonably uniform mapping (symmetry !)
- **Sphere**
  - Problems with concave regions

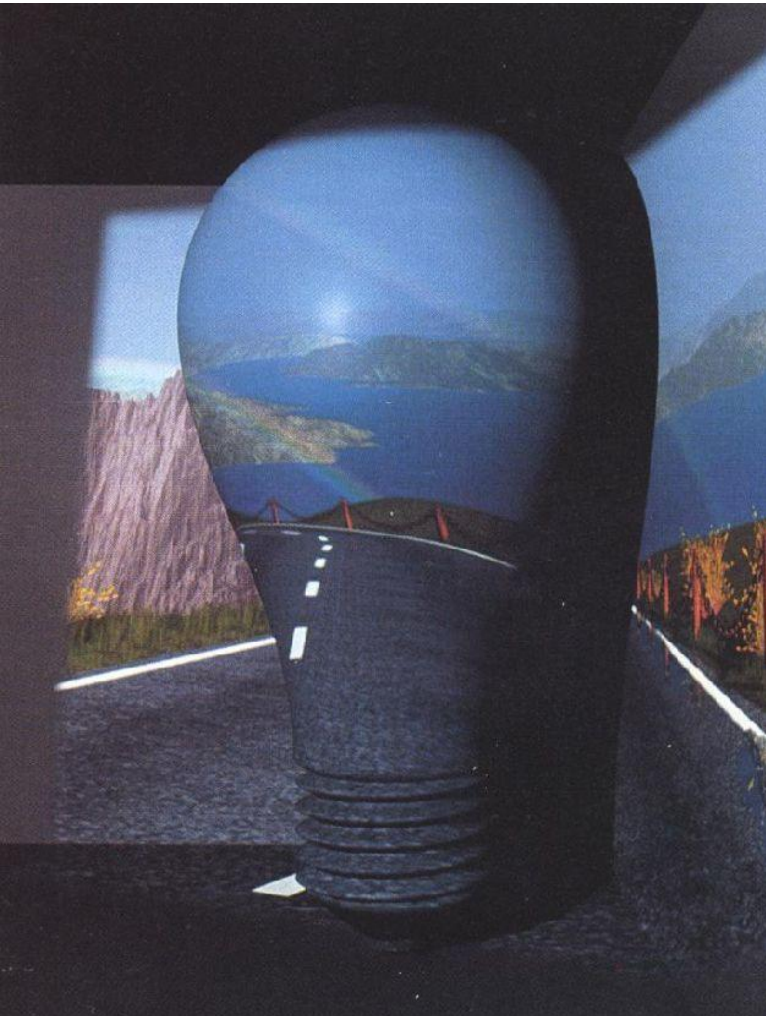


Projective Textures

- **Project texture onto object surfaces**
  - Slide projector
- **Parallel or perspective projection**
- **Use photographs as textures**
- **Multiple images**
  - View-dependent texturing (advanced topic)
- **Perspective mapping**

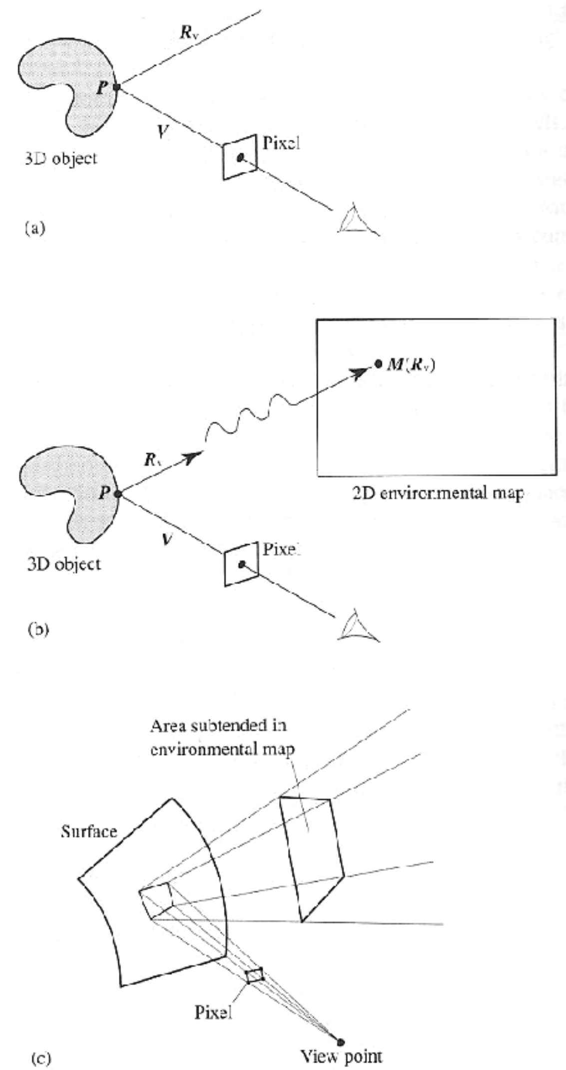


Projective Texturing: Examples



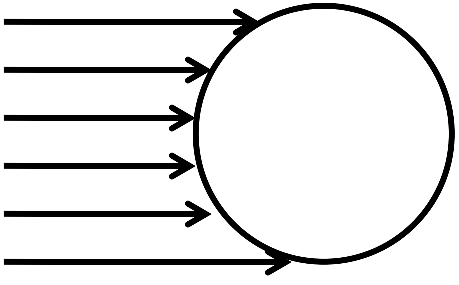
Reflection Mapping

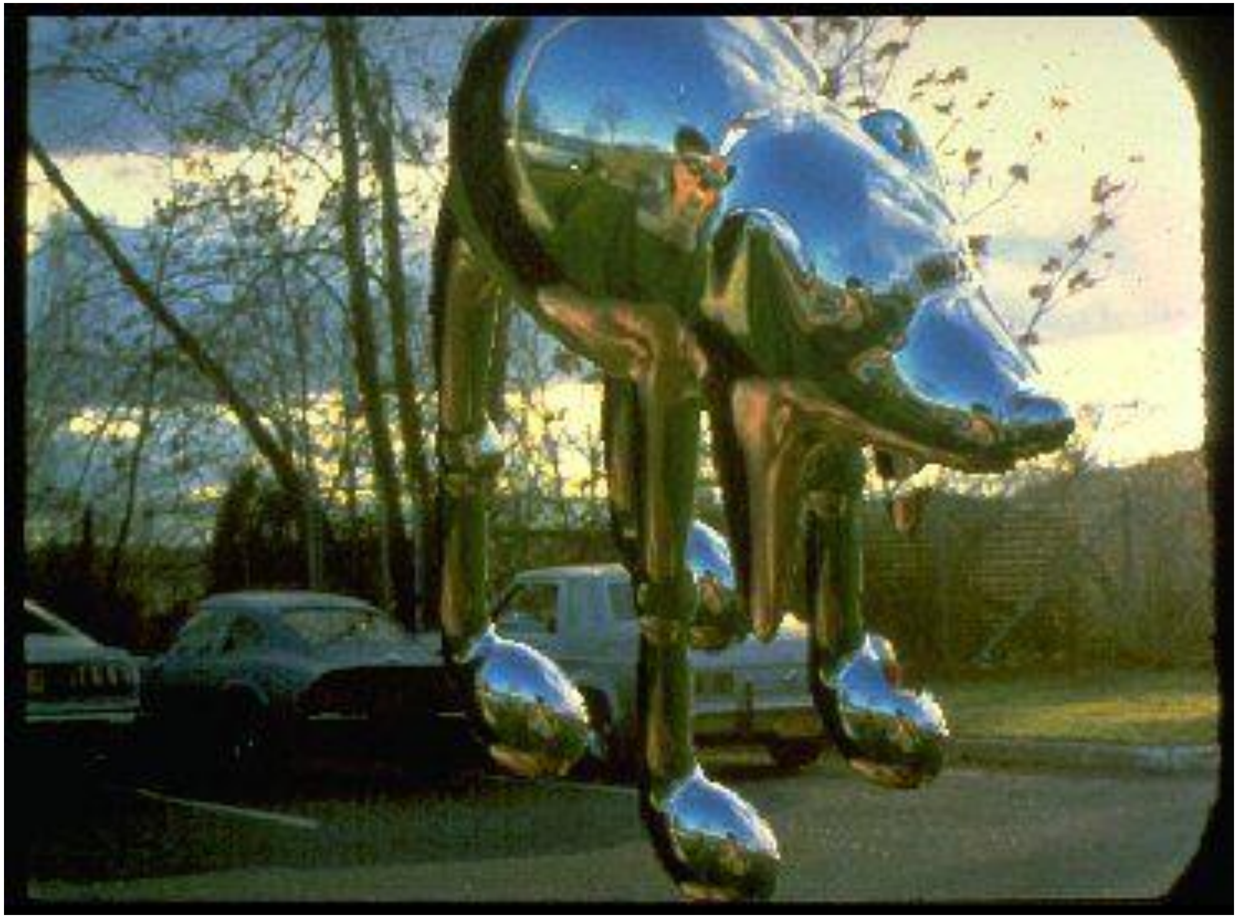
- **Also called “environment mapping”**
- **Reflection map parameterization**
  - Intermediate surface in 2-stage mapping
  - Often cube, sphere, or double paraboloid
- **Assumption: Distant illumination**
  - Parallax-free illumination
  - No self-reflections, distortion of near objects
- **Option: Separate map per object**
  - Often necessary to be reasonably accurate
  - Reflections of other objects
  - Maps must be recomputed after changes
- **Mirror reflections**
  - Surface curvature: beam tracing
  - Map filtering



Reflection Map Acquisition

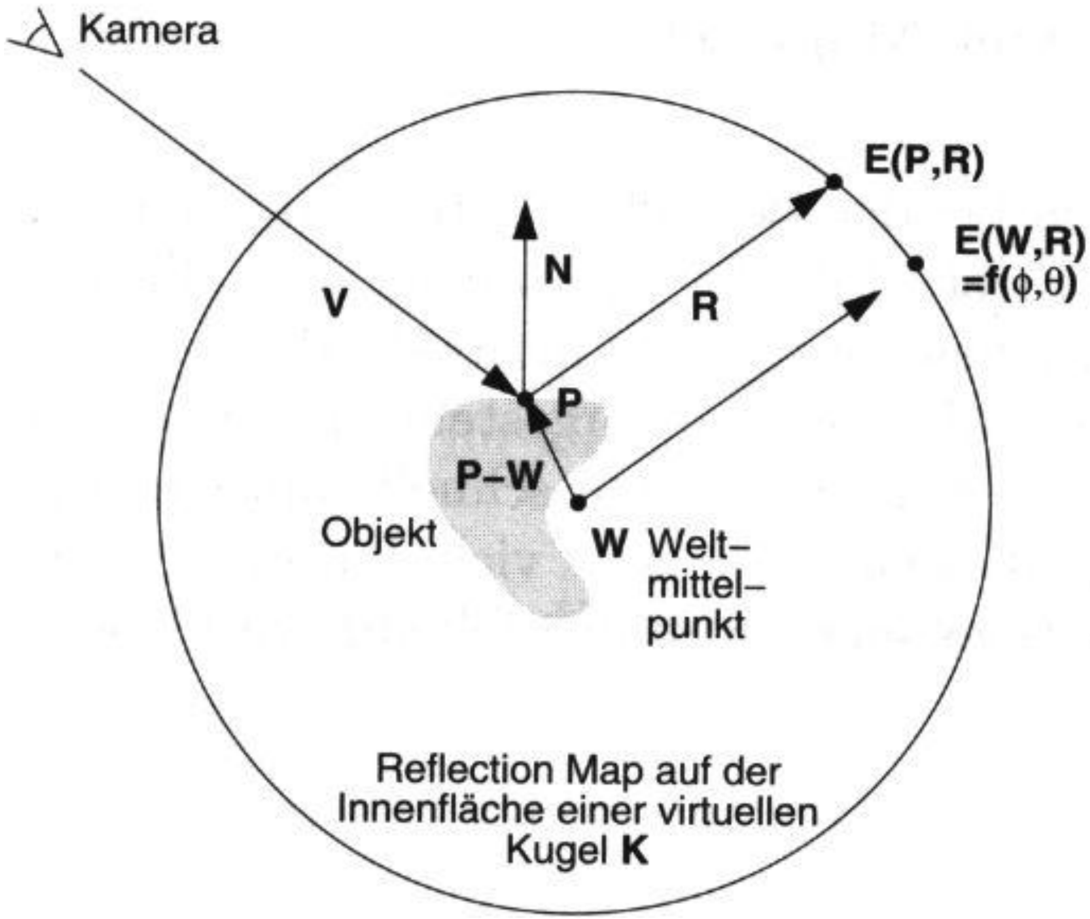
- **Generating spherical maps (original 1982/83)**
  - I.e. photo of a reflecting sphere (gazing ball)





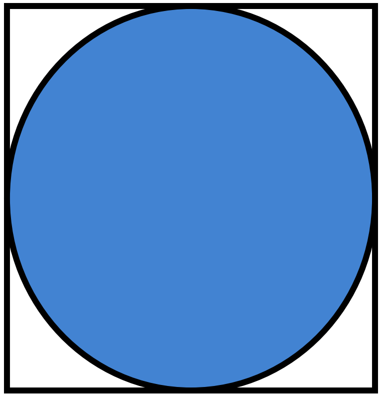
Reflection Map Rendering

- **Spherical parameterization**
- **O-mapping using reflected view ray intersection**

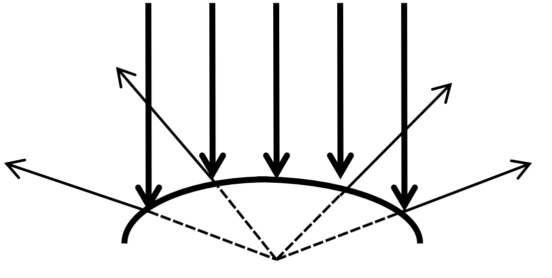


Reflection Map Parameterization

- **Spherical mapping**
  - Single image
  - Bad utilization of the image area
  - Bad scanning on the edge
  - Artifacts, if map and image do not have the same view point

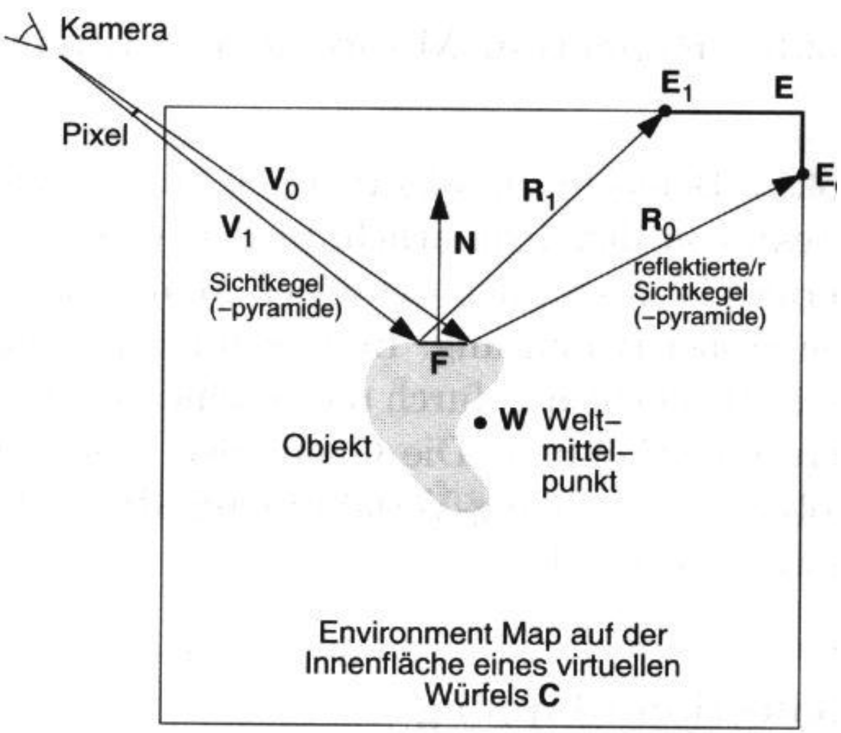


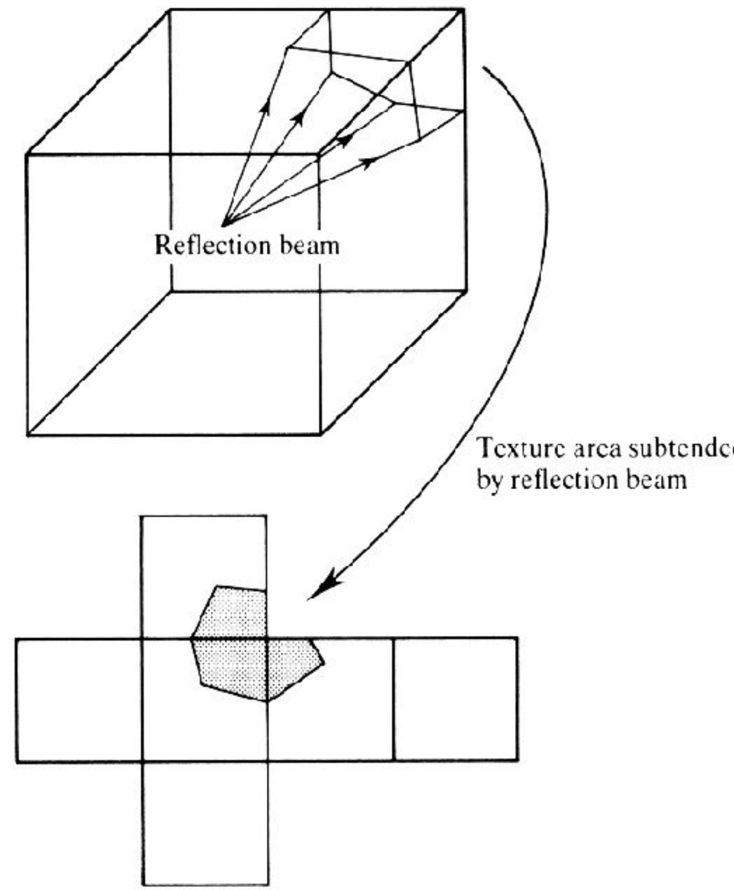
- **Double parabolic mapping**
  - Yields spherical parameterization
  - Subdivide in 2 images (front-facing and back-facing sides)
  - Less bias near the periphery
  - Arbitrarily reusable
  - Supported by OpenGL extensions



Reflection Map Parameterization

- **Cubical environment map, cube map, box map**
  - Enclose object in cube
  - Images on faces are easy to compute
  - Poorer filtering at edges
  - Support in OpenGL





Reflection Mapping Example

Terminator II motion picture

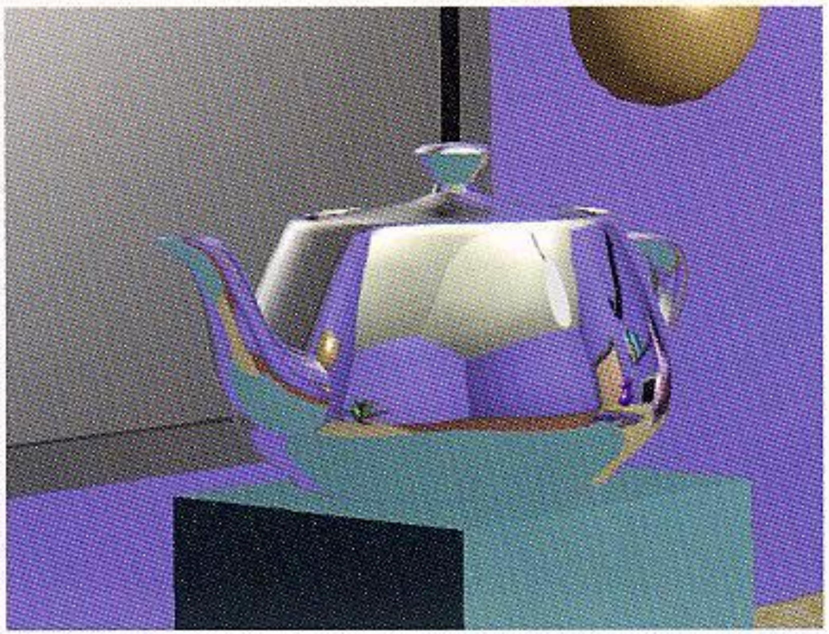
Reflection Mapping Example II

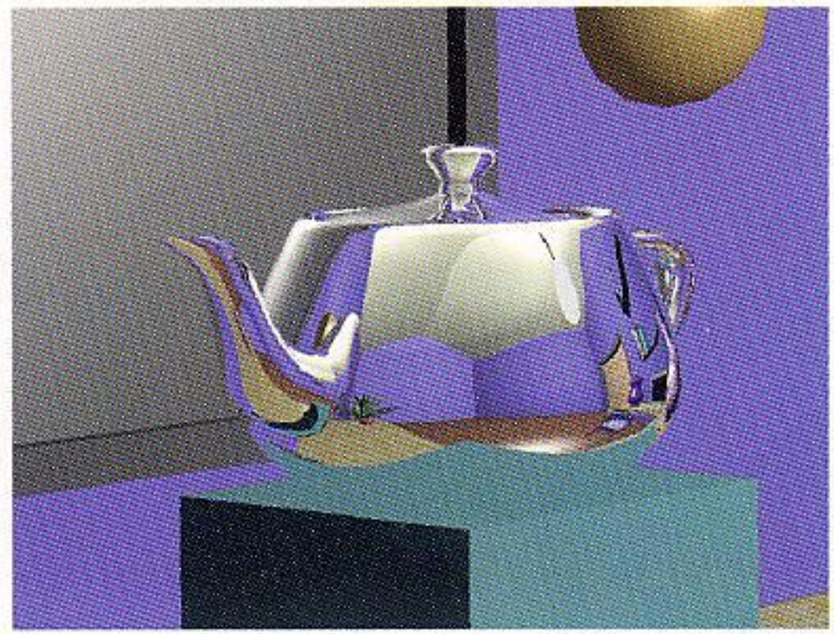
- **Reflection mapping with Phong reflection**
  - Two maps: diffuse & specular
  - Diffuse: index by surface normal
  - Specular: indexed by reflected view vector

RenderMan Companion

Ray Tracing vs. Reflection Map

- **Differences ?**





Recursive Ray Tracing

- **How to fake it with reflection mapping?**

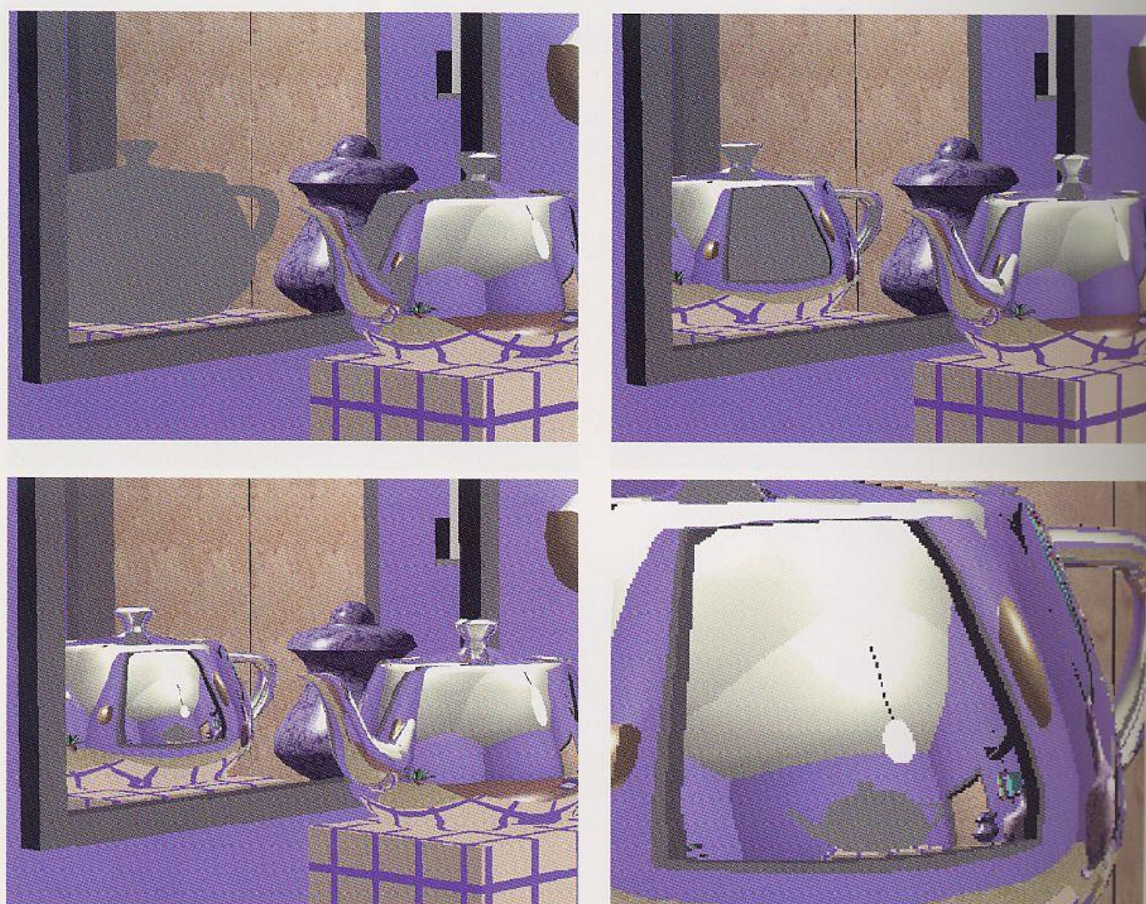
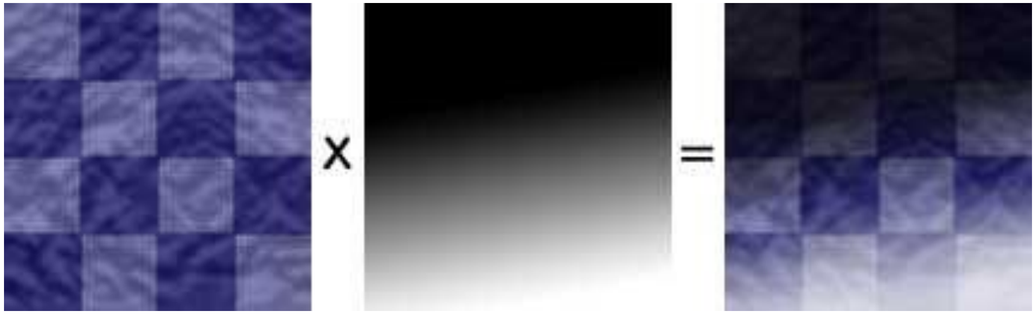


Figure 18.11
A recursive depth demonstration. The trace terminates at depth 2, 3, 4 and 5 (zoom image) respectively. 'Unassigned' pixels are coloured grey. Bad aliasing as a function of recursive depth (the light cable) is apparent.

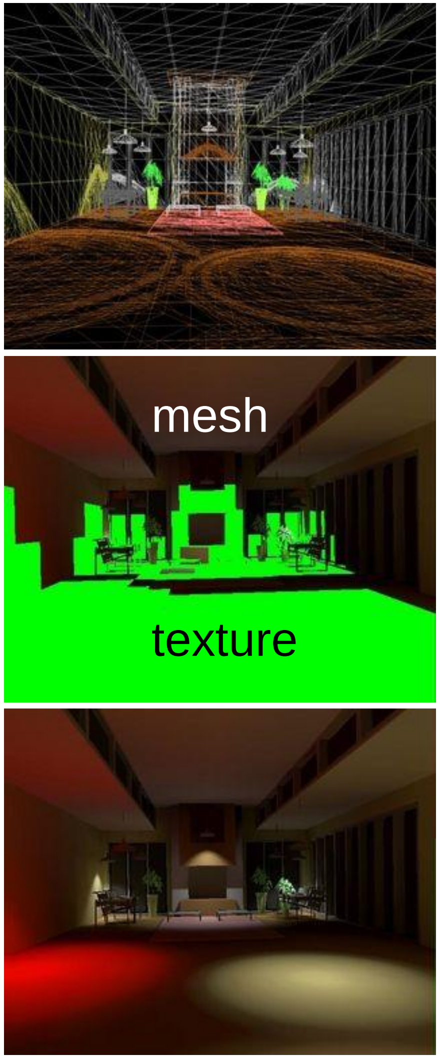
Light Maps

- **Light maps (e.g. in Quake)**
  - Pre-calculated illumination (local irradiance)
    - Often very low resolution: smoothly varying
  - Multiplication of irradiance with base texture
    - Diffuse reflectance only
  - Provides surface radiosity
    - View-independent out-going radiance
  - Animated light maps
    - Animated shadows, moving light spots, etc…



Reflectance Irradiance Radiosity

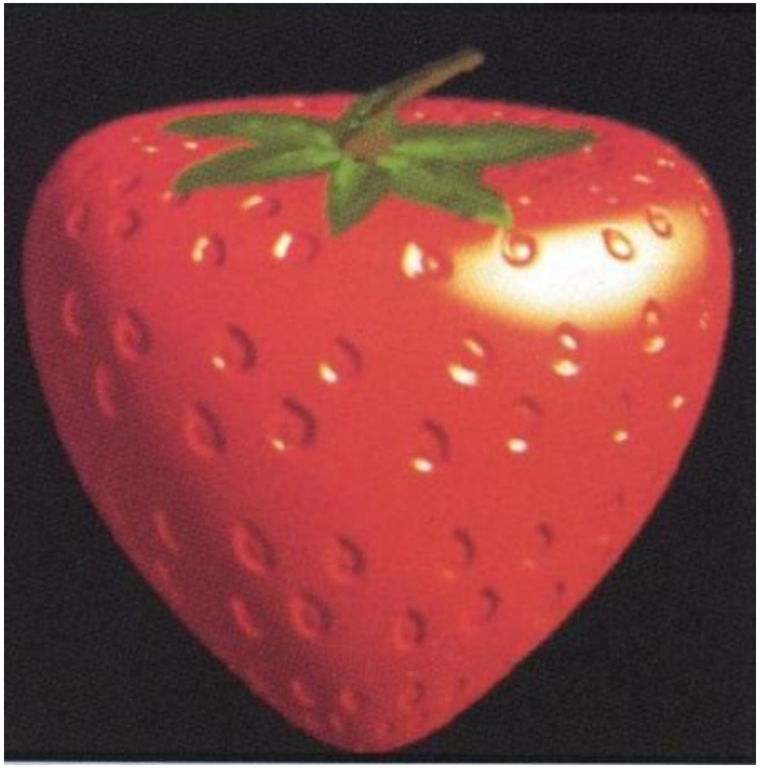
$$B(x) = \rho(x)\,E(x) = \pi L_o(x)$$

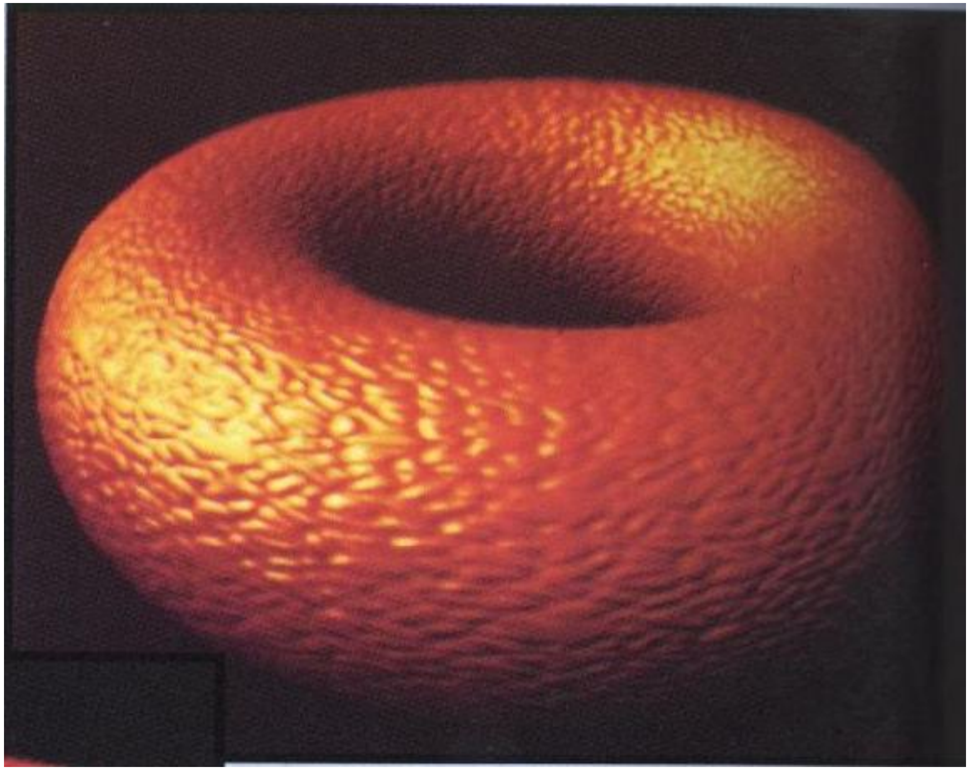


Representing radiosity in a mesh or texture

Bump Mapping

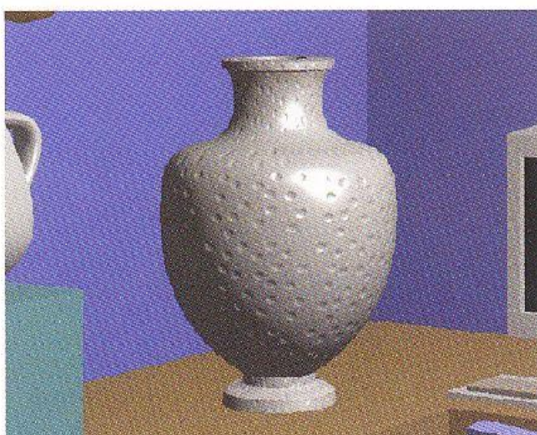
- **Modulation of the normal vector**
  - Surface normals changed only
    - Influences shading only
    - No self-shadowing, contour is **not** altered

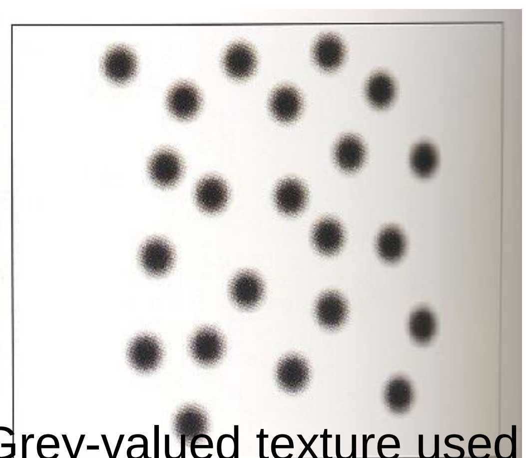


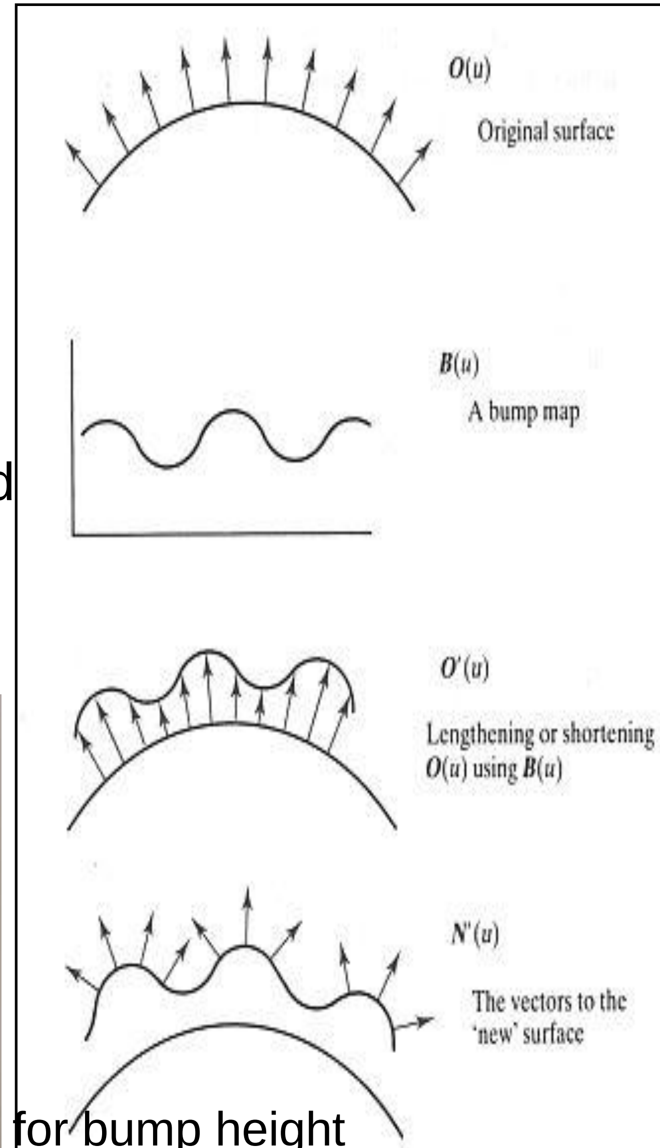


Bump Mapping

- **Original surface:** *O(u,v)*
  - Surface normals are known
- **Bump map:** *B(u,v)* ϵ *R*
  - Surface is offset in normal direction according to bump map intensity
  - New normal directions *N'(u,v)* are calculated based on virtually displaced surface *O'(u,v)*
  - Original surface is rendered with new normals *N'(u,v)*







Grey-valued texture used for bump height

Bump Mapping

$$O'(u,v) = O(u,v) + B(u,v)\frac{N}{|N|}$$

– Normal is cross-product of derivatives:

$$O'_u = O_u + B_u \frac{N}{|N|} + B\left(\frac{N}{|N|}\right)_u$$

$$O'_v = O_v + B_v \frac{N}{|N|} + B\left(\frac{N}{|N|}\right)_v$$

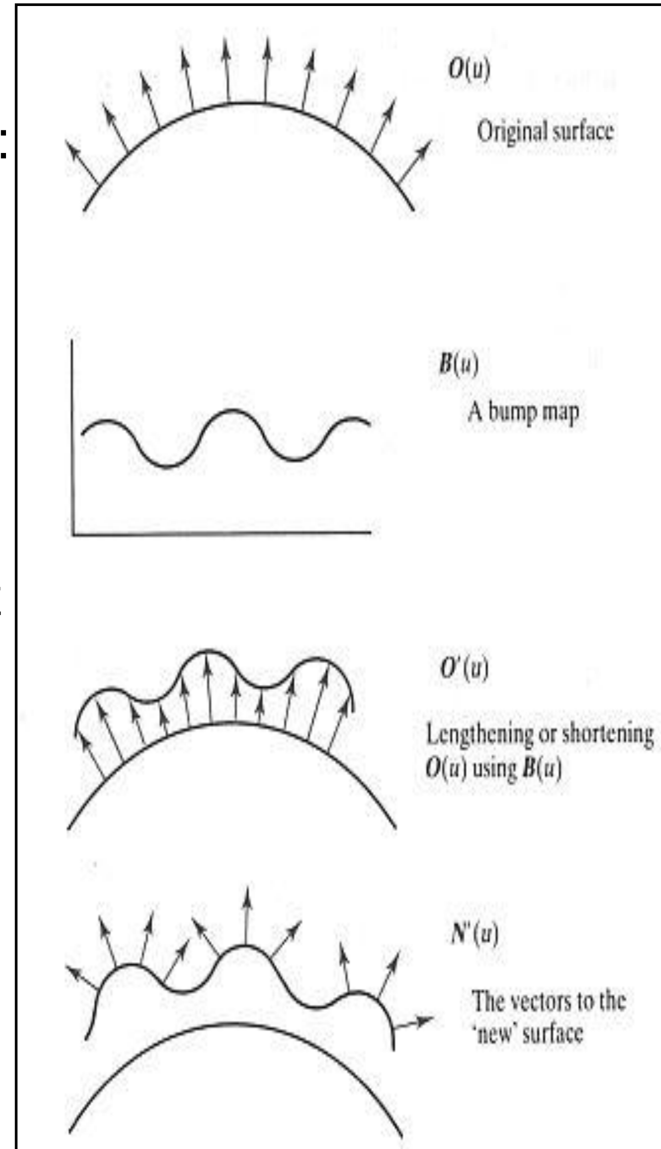
– If B is small (i.e. the bump map displacement function is small compared to its spatial extent) the last term in each equation can be ignored

$$N'(u,v) = O_u \times O_v + B_u\left(\frac{N}{|N|} \times O_v\right) + B_v\left(O_u \times \frac{N}{|N|}\right) + B_u B_v\left(\frac{N \times N}{|N|^2}\right)$$

– The first term is the normal to the surface and the last is zero, giving:

$$D = B_u(N \times O_v) - B_v(N \times O_u)$$

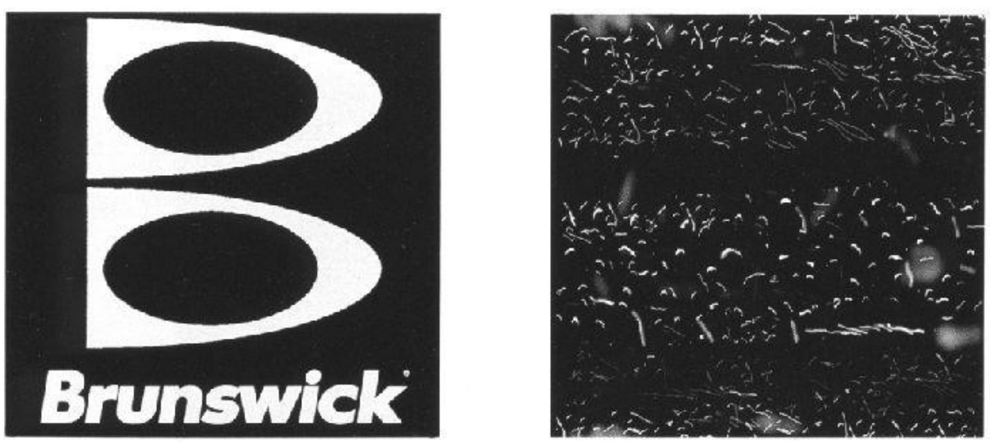
$$N' = N + D$$

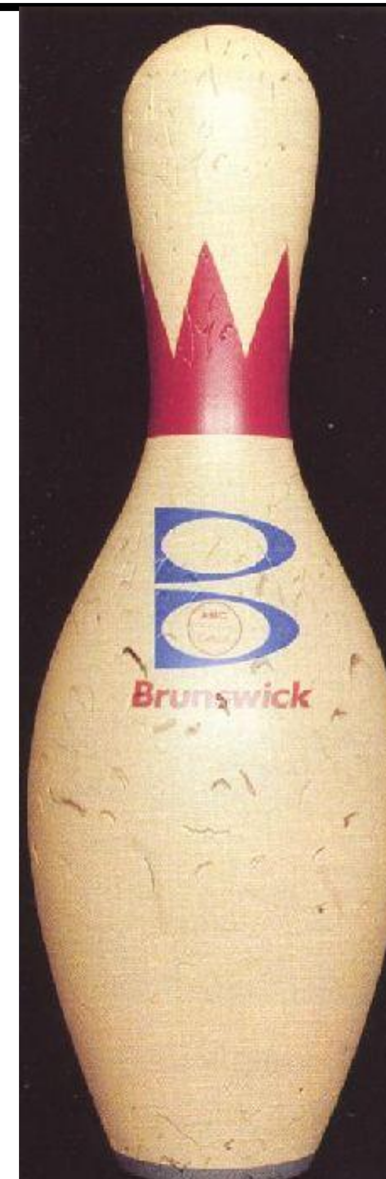


Texture Examples

- **Complex optical effects**
  - Combination of multiple texture effects

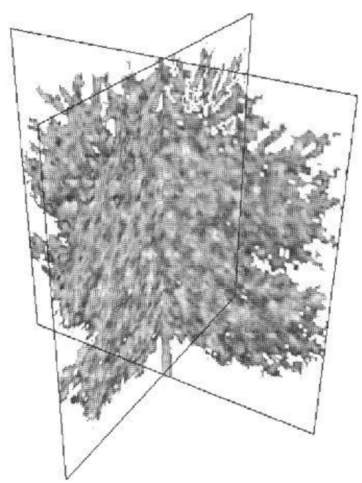
RenderMan Companion

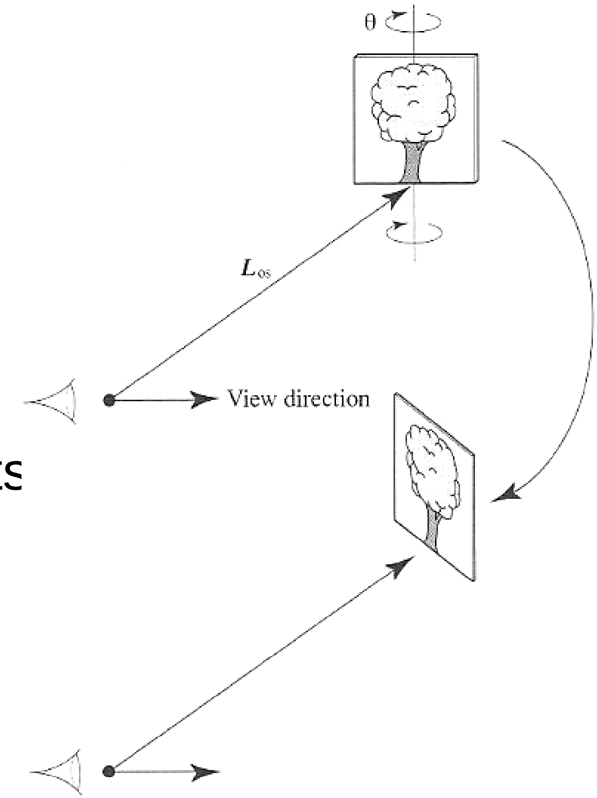




Billboards

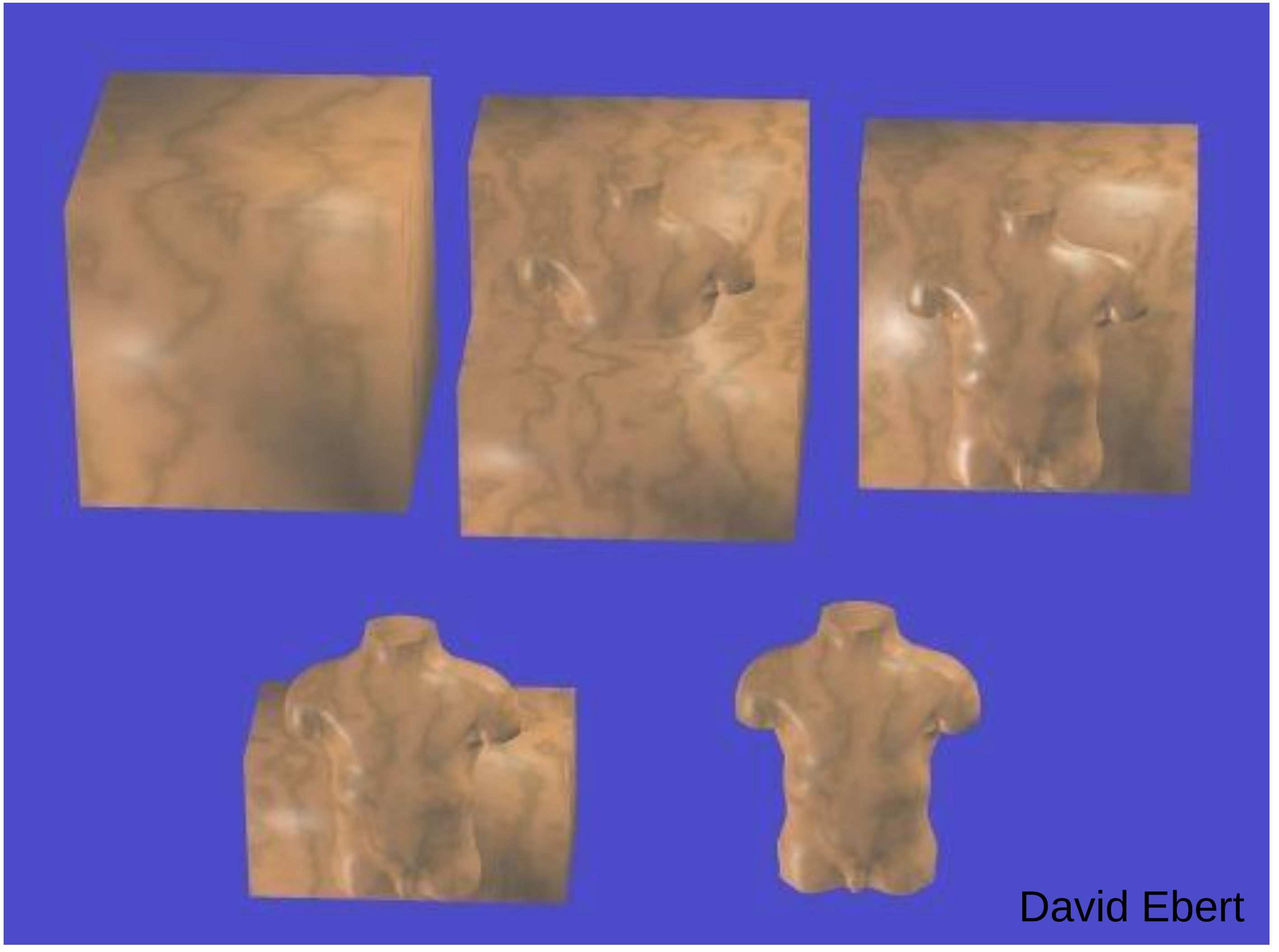
- **Single textured polygons**
  - Often with opacity texture
  - Rotates, always facing viewer
  - Used for rendering distant objects
  - Best results if approximately radially or spherically symmetric
- **Multiple textured polygons**
  - Azimuthal orientation: different view-points
  - Complex distribution: trunk, branches, …





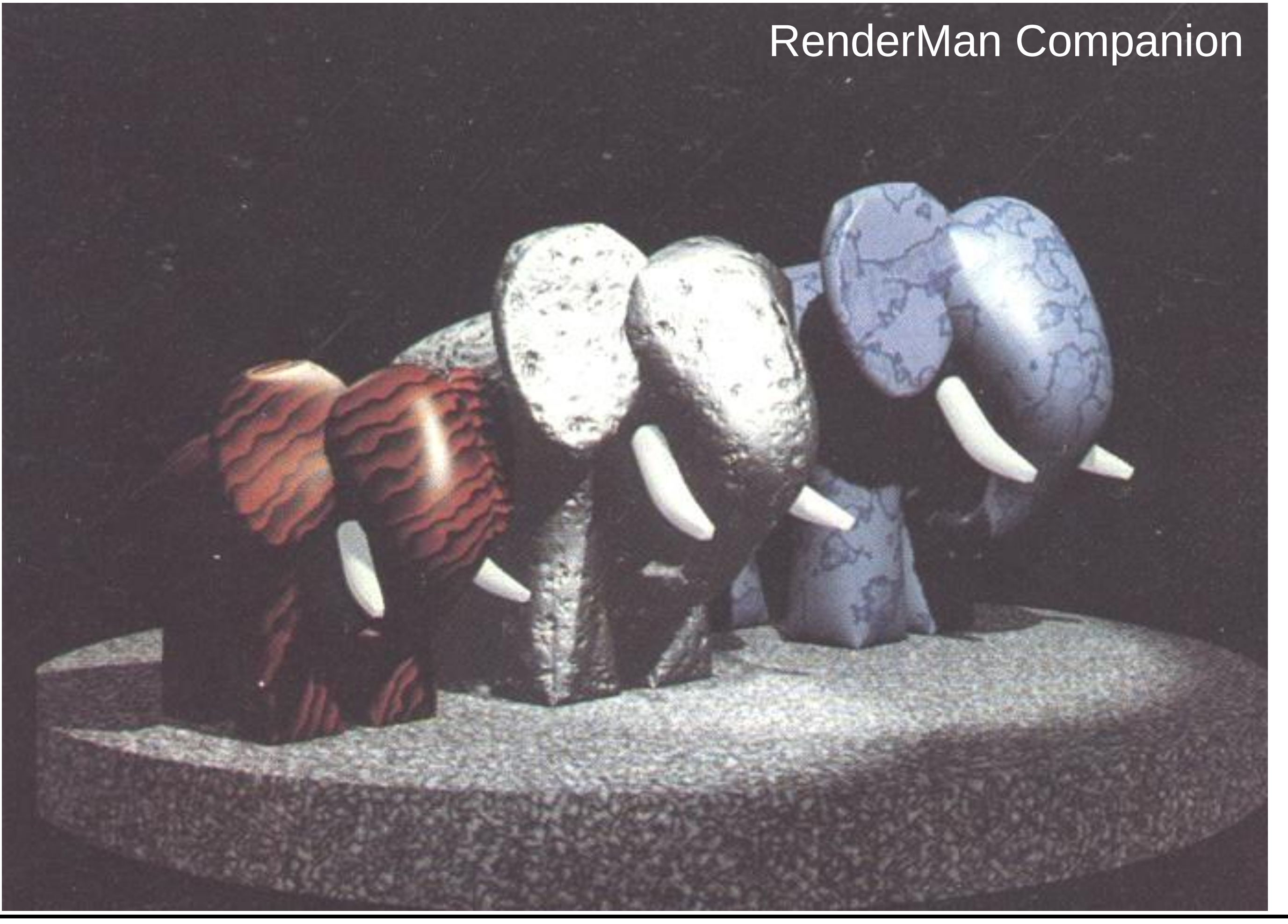
3-D Textures

- **“Carving object shape out of material block”**



Texture Examples

- **Solid 3D textures (wood, marble)**
- **Bump map (middle)**



Part II

Procedural Methods

Texture Maps | Procedural Textures

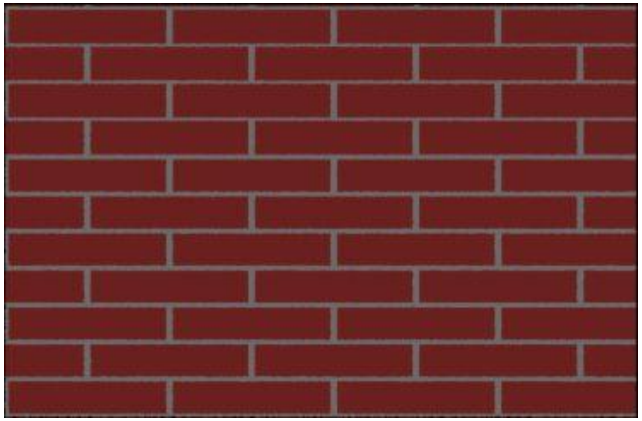
- **Texture maps: paintings, photos, videos, simulation...**
  - Simple acquisition
  - Illumination “frozen” during acquisition
  - Limited resolution, aliasing
  - High memory requirements
  - Mapping issues
- **Procedural textures**
  - Non-trivial programming
  - Flexibility & parametric control
  - Unlimited resolution
  - Anti-aliasing possible
  - Low memory requirements
  - Low-cost visual complexity
  - Can adapt to arbitrary geometry

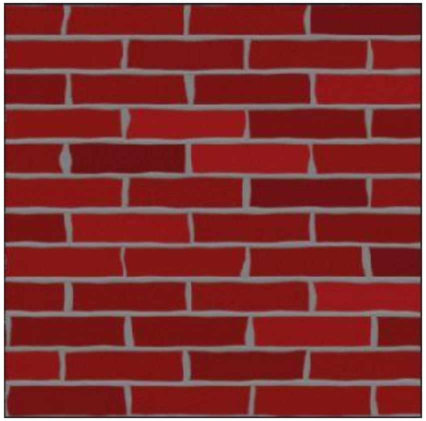
Procedural Textures

- **Function of some shading parameter**
  - E.g. world space, texture coordinates, ...
- **Texturing: evaluation of function on object surface**
  - Ray tracing: at intersection point with surface
  - Must be able to evaluate at random position efficiently
- **Observation: textures of natural objects**
  - Similarity between patches at different locations
    - Repetitiveness, coherence (e.g. skin of a tiger or zebra)
  - Similarity on different resolution scales
    - Self-similarity
  - But never completely identical
    - Additional disturbances, turbulence, noise
- **Goal: generic procedural texture function**
  - Mimics statistical properties of natural textures
  - Purely empirical approach
    - Looks convincing, but has nothing to do with material's physics

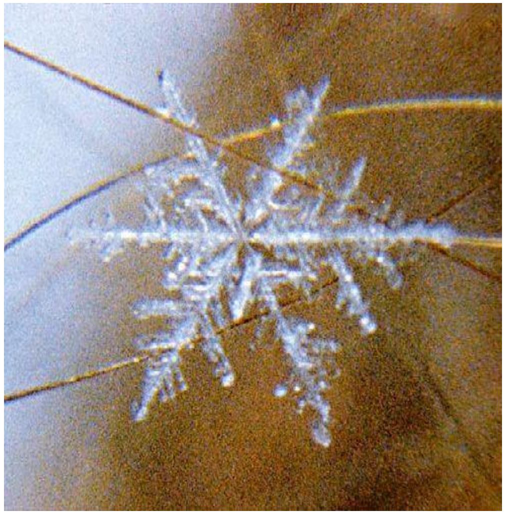
Texture Examples

- **Translational similarity**

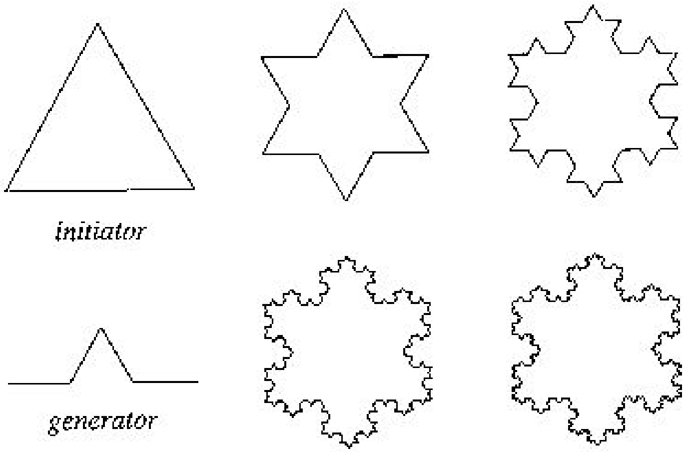




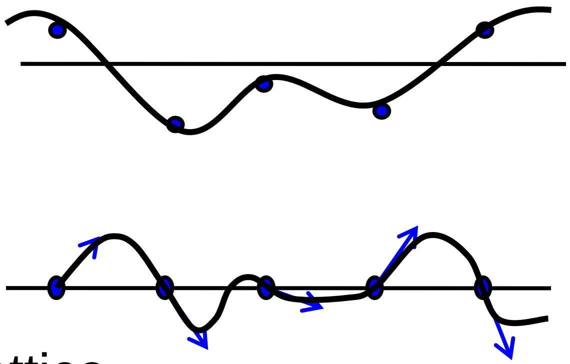
- **Similarity on different scales**



Romanesco broccoli [Wikipedia]



3D / Solid Noise: Perlin Noise

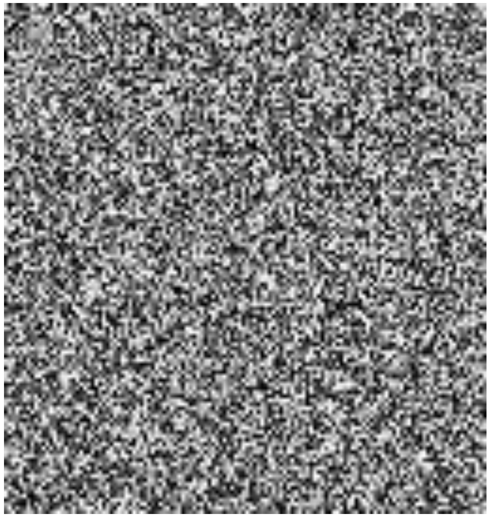


- **Noise(x,y,z)**
  - Statistical invariance under rotation
  - Statistical invariance under translation
  - Roughly one specific frequency
- **Integer lattice (i,j,k)**
  - Fixed fundamental frequency of ~1 Hz over lattice
  - Don't store all values – use a hash function to randomize and look up from a fixed-size table
  - Value noise: Random value at lattice
  - Gradient noise: Random gradient vector at lattice point Q: G(Q)
    - Value at point P: G·(P-Q)
  - Tri-linear interpolation or cubic interpolation
    - Hermite spline → later
- **Unlimited domain due to lattice and hashing**
- **Also see**
  - http://www.noisemachine.com/talk1/
  - http://www.cs.cmu.edu/~mzucker/code/perlin-noise-math-faq.html

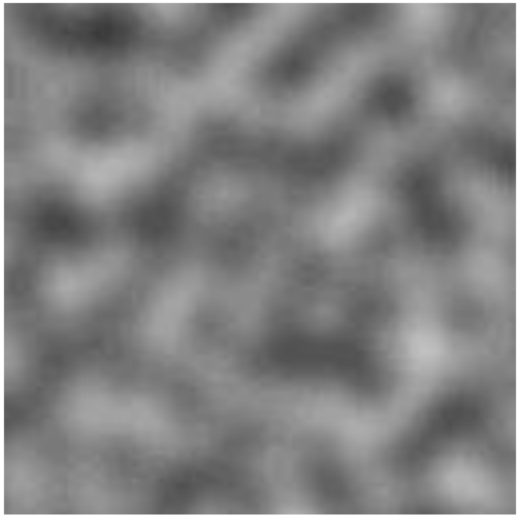
Noise vs. Noise

- **Gradient noise better than value noise**
  - Less regularity artifacts
  - More high frequencies in noise spectrum
  - Even tri-linear interpolation produces good results

- **Comparison between random values and Perlin noise**



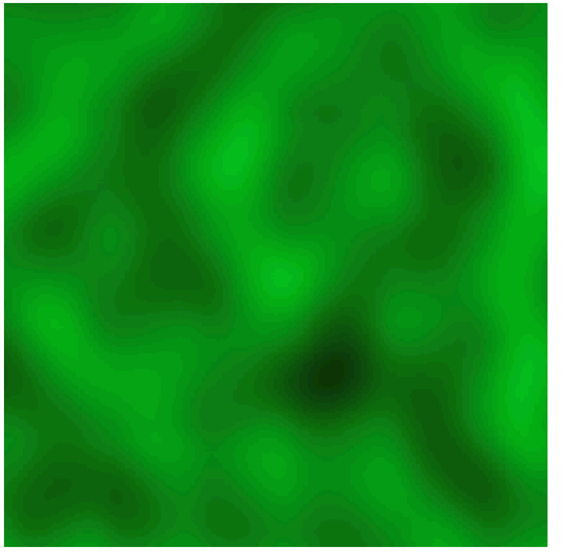
Random values
at each pixel

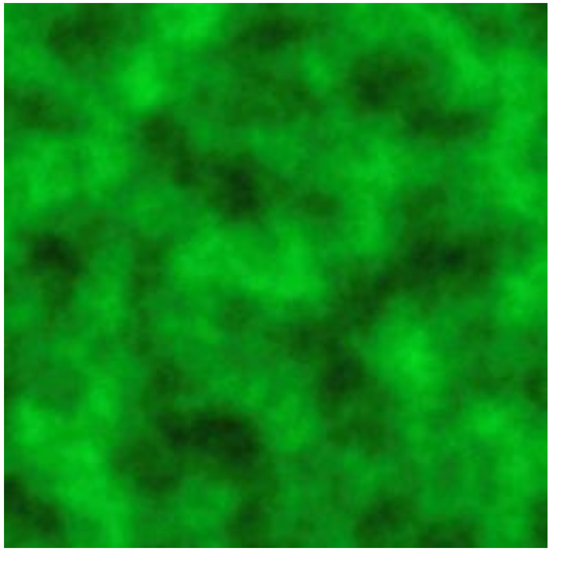


Gradient noise

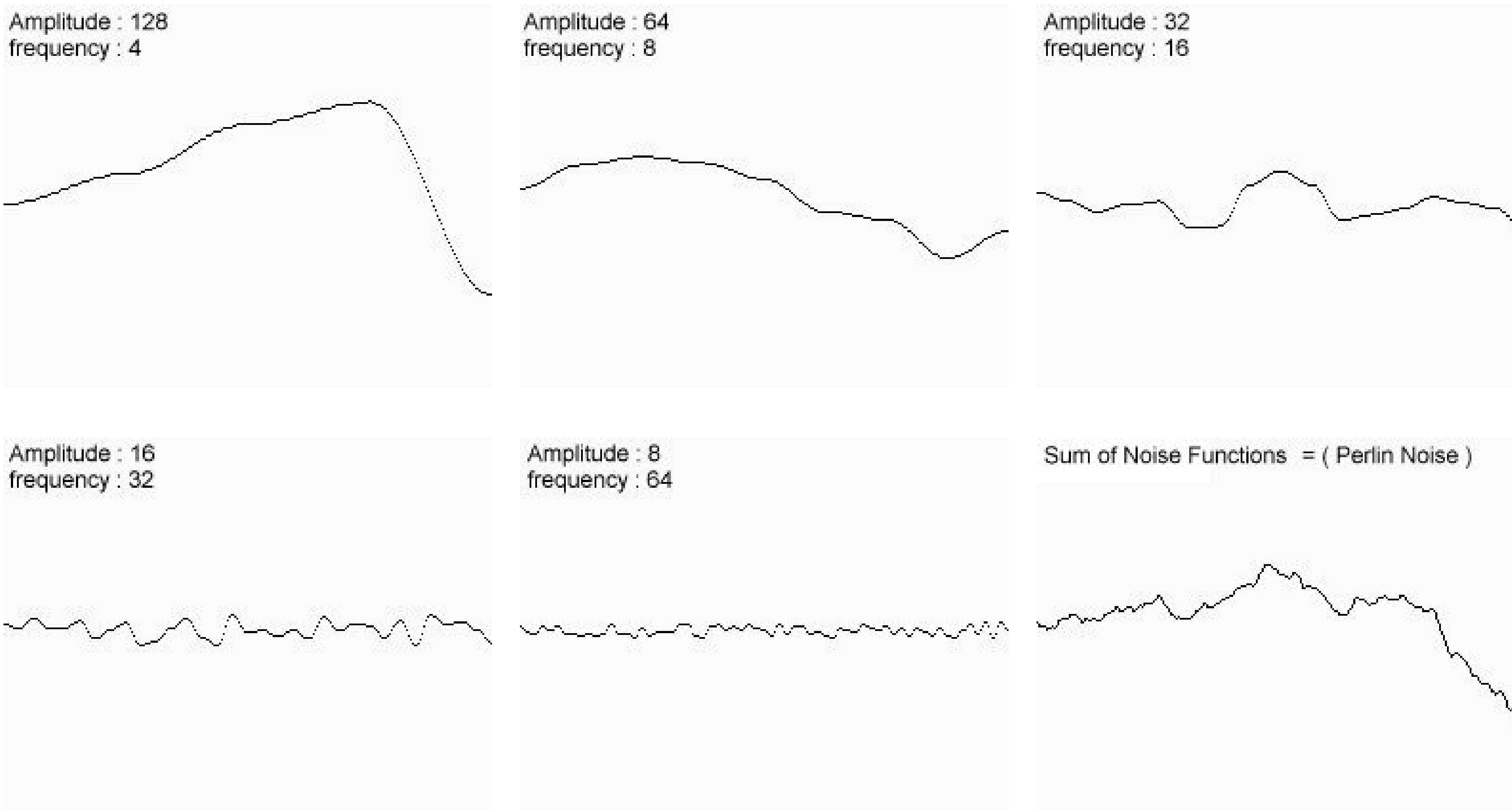
Turbulence Function

- **Noise function**
  - Single spike in frequency spectrum
- **Natural textures**
  - Decreasing power spectrum towards high frequencies
- **Turbulence from noise**
  - $Turbulence(x) = \sum_{i=0}^{k} |a_i * noise(f_i x)|$
    - Frequency: $f_i = 2^i$
    - Amplitude: $a_i = 1 / p^i$
    - Persistence: *p* typically *p*=2
  - Summation truncation
    - 1st term: noise(x)
    - 2nd term: noise(2x)/2
    - …
    - Until period $(1/f_k)$ < 2 pixel-size (band limit)
  - Power spectrum : $a_i = 1 / f_i$
  - Brownian motion: $a_i = 1 / f_i^2$

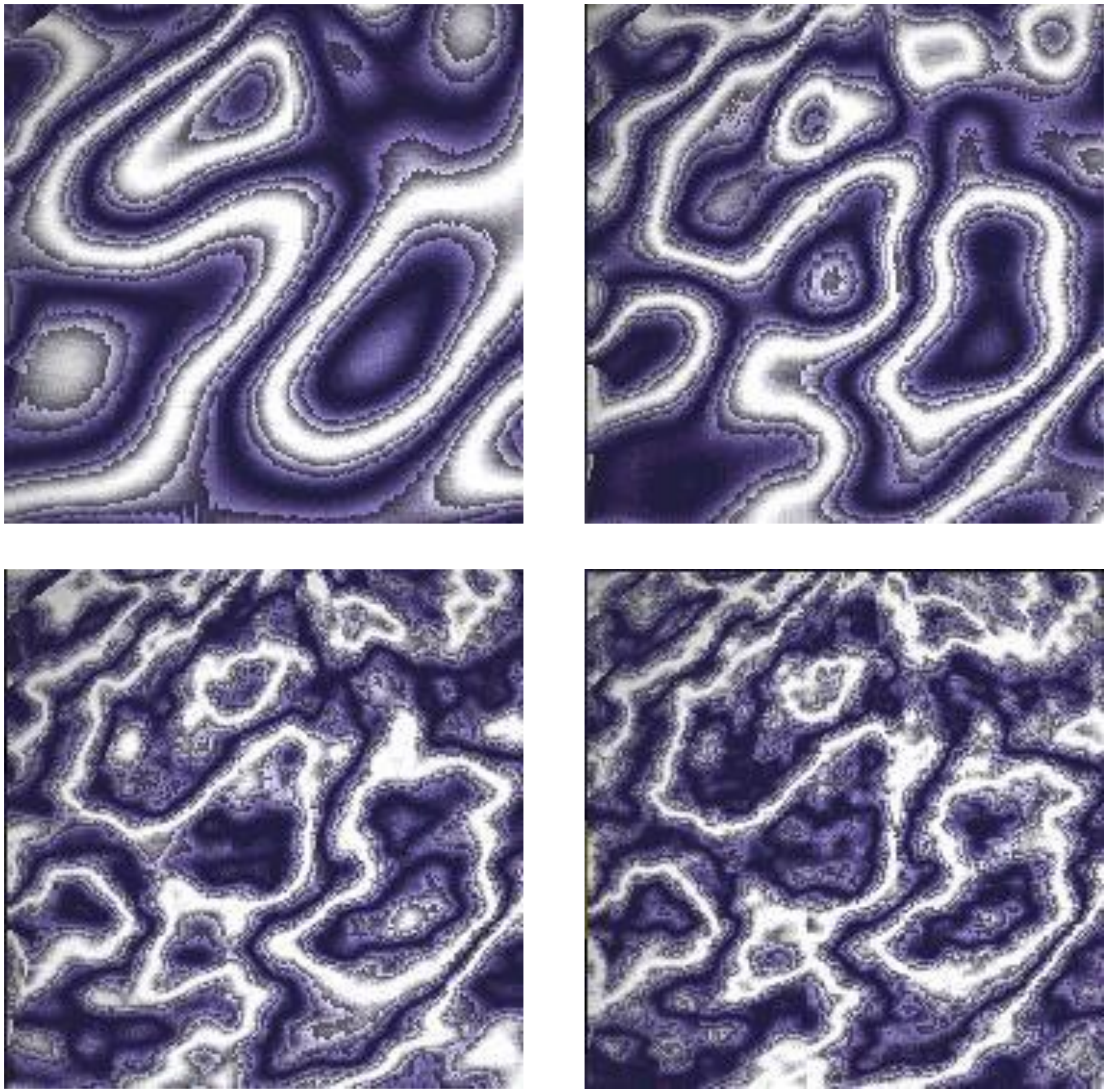




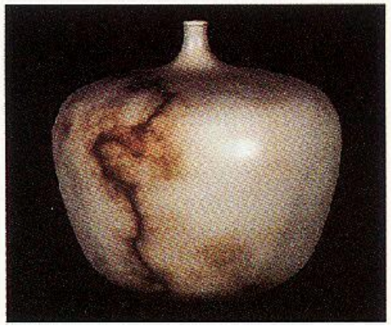
Synthesis of Turbulence (1D)



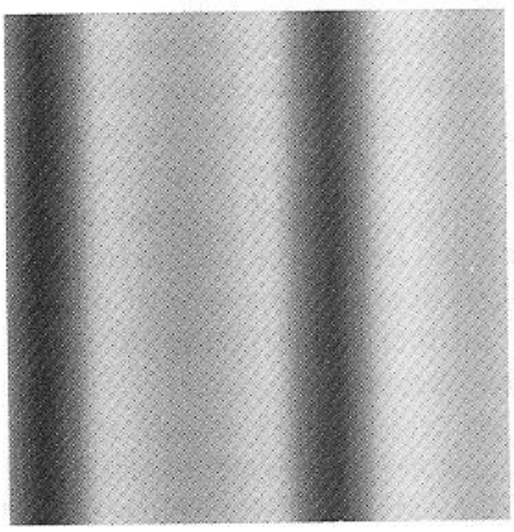
Synthesis of Turbulence (2D)

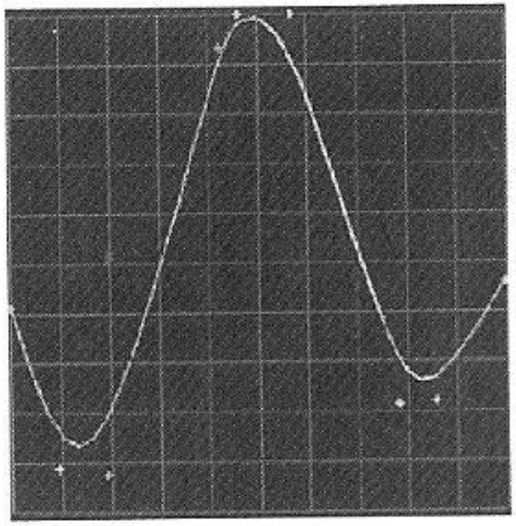


Example: Marble Texture Function



- **Overall structure: alternating layers of white and colored marble**
  - $f_{marble}(x,y,z)$:= marble_color(sin(x))
  - marble_color : transfer function (see lower left)
- **Realistic appearance: simulated turbulence**
  - $f_{marble}(x,y,z)$:= marble_color(sin(x+turbulence(x,y,z)))
- **Moving object: turbulence function also transformed**



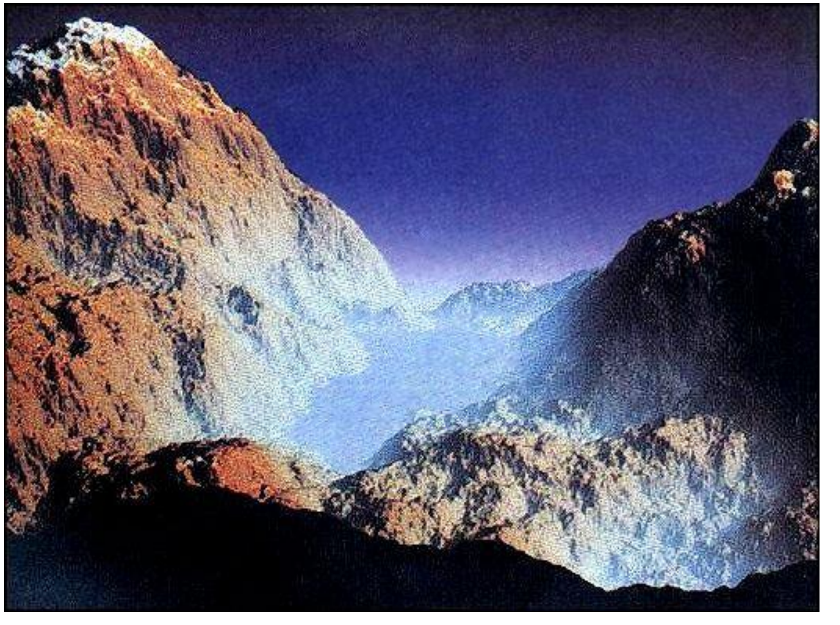


Further Procedural Texturing Applications

- **Bark**
  - Turbulated sawtooth function
  - Bump mapping
- **Clouds**
  - White blobs
  - Turbulated transparency along edge
  - Transparency mapping
- **Animation**
  - Vary procedural texture function's parameters over time

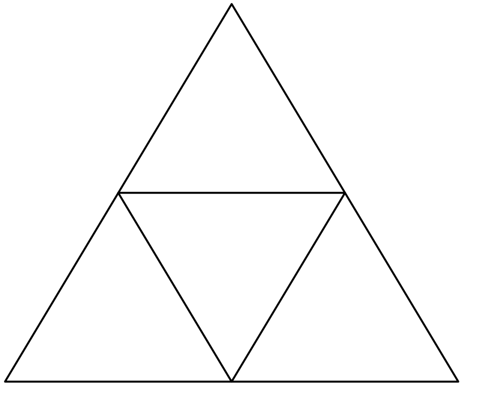
Fractal Landscapes

- **Procedural generation of geometry**
- **Complex geometry at virtually no memory cost**
  - Can be difficult to ray trace !!



Fractal Landscapes

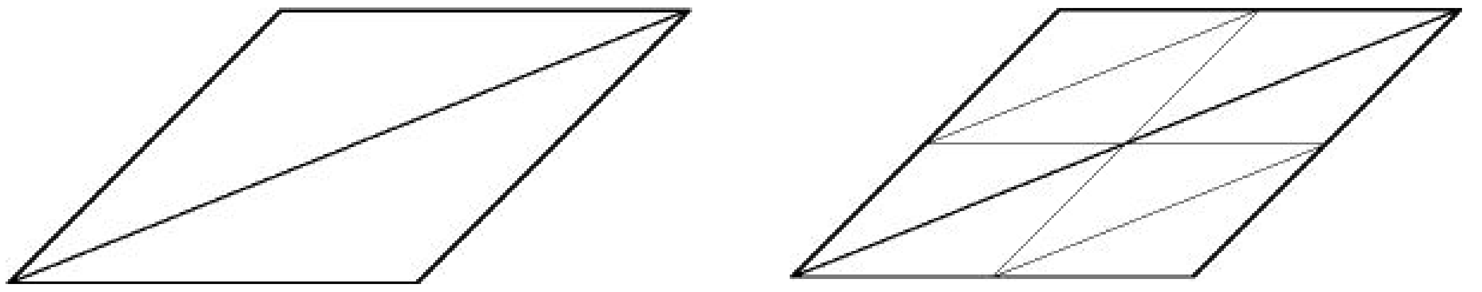
- **Coarse triangle mesh approximation**
- **1:4 triangle subdivision**
  - Vertex insertion at edge-midpoints
- **New vertex perturbation**
  - Random displacement along normal
  - Scale of perturbation depends on subdivision level
    - Decreasing power spectrum
    - Parameter models surface roughness



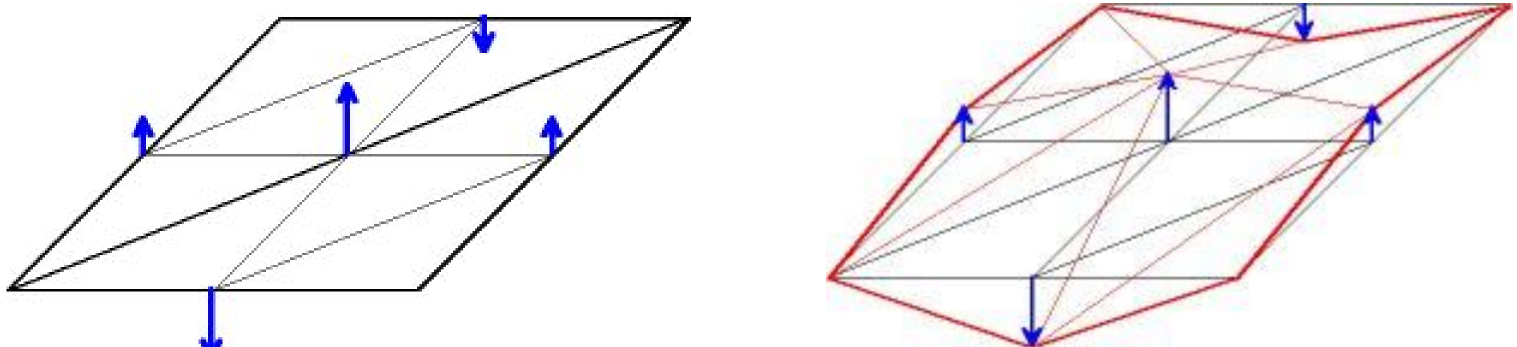
- **Recursive subdivision**
  - Level of detail (LOD) determined by # subdivisions
- **All done inside renderer !**
  - LOD generated locally when/where needed (bounding box test)
  - Minimal I/O cost (coarse mesh only)

Fractal Landscapes

- **Triangle subdivision**
  - Insert new vertices at edge midpoints
  - 1:4 triangle subdivision



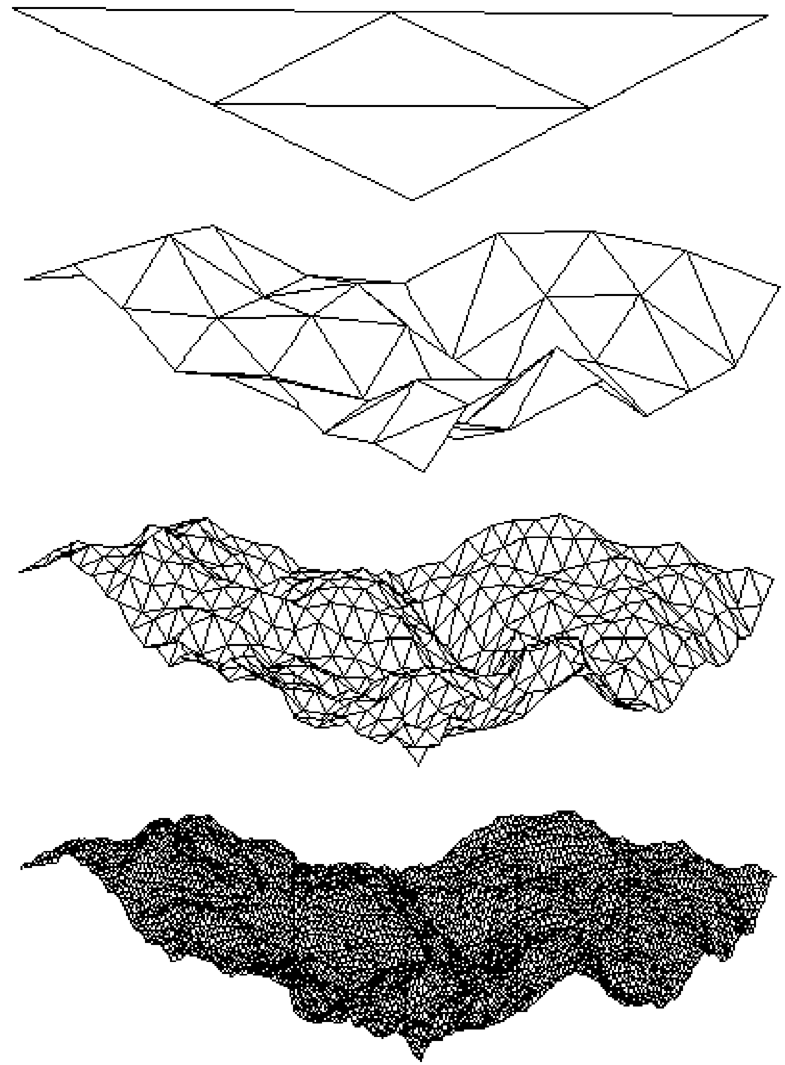
- **Vertex displacement**
  - Along original triangle normal

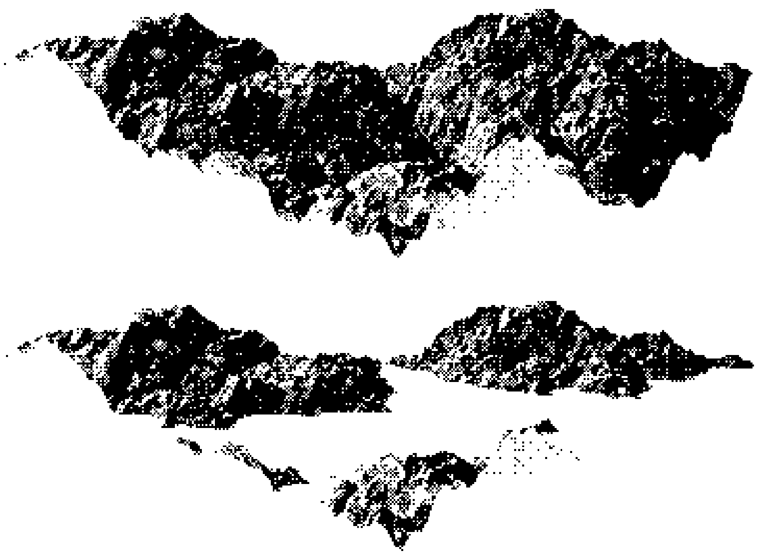


Courtesy http://www.uni-paderborn.de/SFB376/projects/a2/zBufferMerging/

Fractal Landscape Generation

- **Base mesh**
- **Repeated subdivision & vertex displacement**
- **Shading + Water surface + Fog + …**





Courtesy http://www.uwp.edu/academic/computer.science/morris.csci/CS.320/Week.11/Ch11b.www/Ch11b.html

Fractal Landscape Ray Tracing

- **Fractal terrain generated on-the-fly**
- **Problem: where is the ray-surface interaction ?**
  – Triangle mesh not a-priori known
- **Solution: bounding boxes**
  – Maximum possible bounding box around each triangle
  – Decreasing displacement amplitude: finite bounding box
- **Algorithm**
  – Intersect ray with bounding box
  – If hit, subdivide corresponding triangle
  – Compute bounding boxes of 4 new triangles
  – Test against 4 new bounding boxes
  – Iterate until termination criterion fulfilled (LOD / pixel size)