Rendering Competition Theme

- **Four rendering competition themes**

- **Vote for your favorite before *Sunday* 23:59 *December 3rd***

- **Think about the scene you want to render and how it could fit together with the theme you vote for.**

Vote for your favorite!

Journey to the Unknown

Whispers of Tomorrow

Chaos in Harmony

Lost in Translation

Computer Graphics

- Texturing -

Philippe Weier

Alexander Rath

Philipp Slusallek

Overview

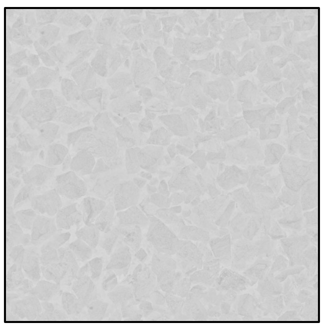
- **Texture**
- **Image Textures**
- **Procedural Textures**
- **Texture Mapping**

TEXTURE

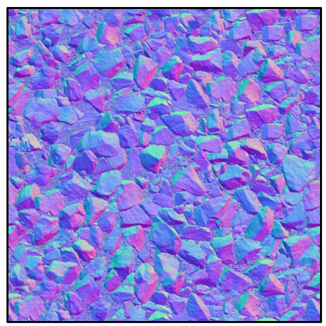
Texture

- **Textures modify the input for shading computations**
  - Either via (painted) images textures or procedural functions
- **Example texture maps for**
  - Reflectance, normals, shadows,reflections, essentially anything, …

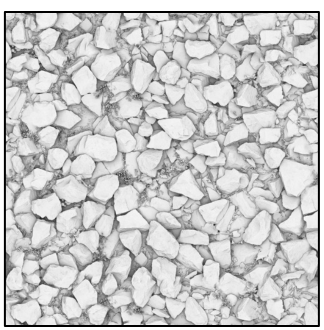
Roughness



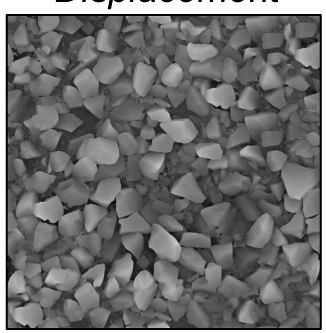
Normals



Ambient Occlusion



Displacement



Albedo

Polyhaven : https://polyhaven.com/

Texture

- **Two BSDFs only, all the variations comes from textures**

Definition: Textures

- **Textures map texture coordinates to shading values**
  - Input: 1D/2D/3D/4D texture coordinates
    - Explicitly given or derived via other data (e.g., position, direction, …)
  - Output: Scalar or vector value
- **Modified values in shading computations**
  - Reflectance
    - Changes the diffuse or specular reflection coefficient (k_d, k_s)
  - Geometry and Normal (important for lighting)
    - Displacement mapping $P' = P + \Delta P$
    - Normal mapping $N' = N + \Delta N$
    - Bump mapping $N' = N(P + tN)$
  - Opacity
    - Modulating transparency (e.g., for fences in games)
  - Illumination
    - Light maps, environment mapping, reflection mapping
  - Anything else …

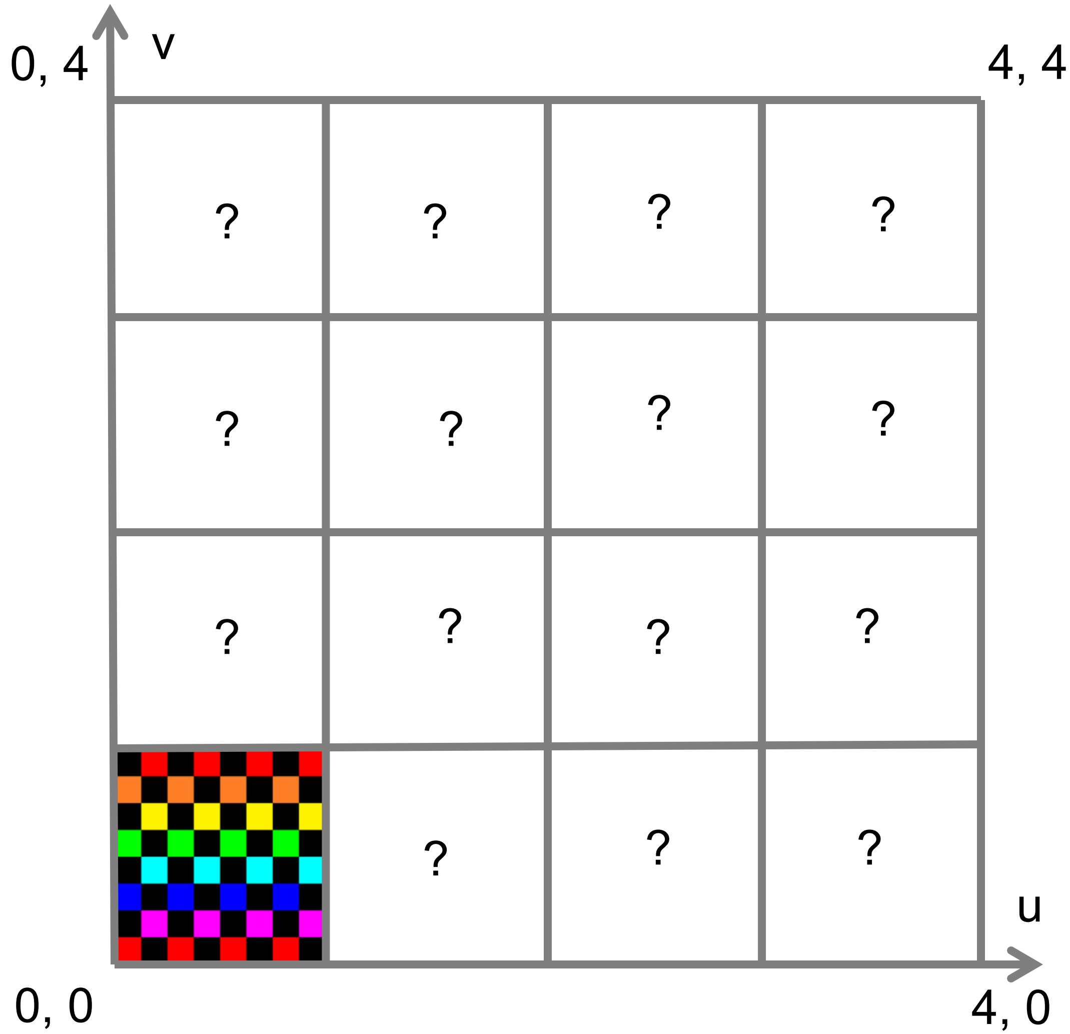
IMAGE TEXTURES

Image Textures

- **Image textures**
  - Return the color of the image at a given point
  - Point defined by mapping the texture coordinates $[0,1]^n$ to the entire image
  - Images may be 1D (line of pixels), 2D, and 3D (stacks of images)
  - Coordinates outside of $[0,1]^2$ can be mapped in different modes

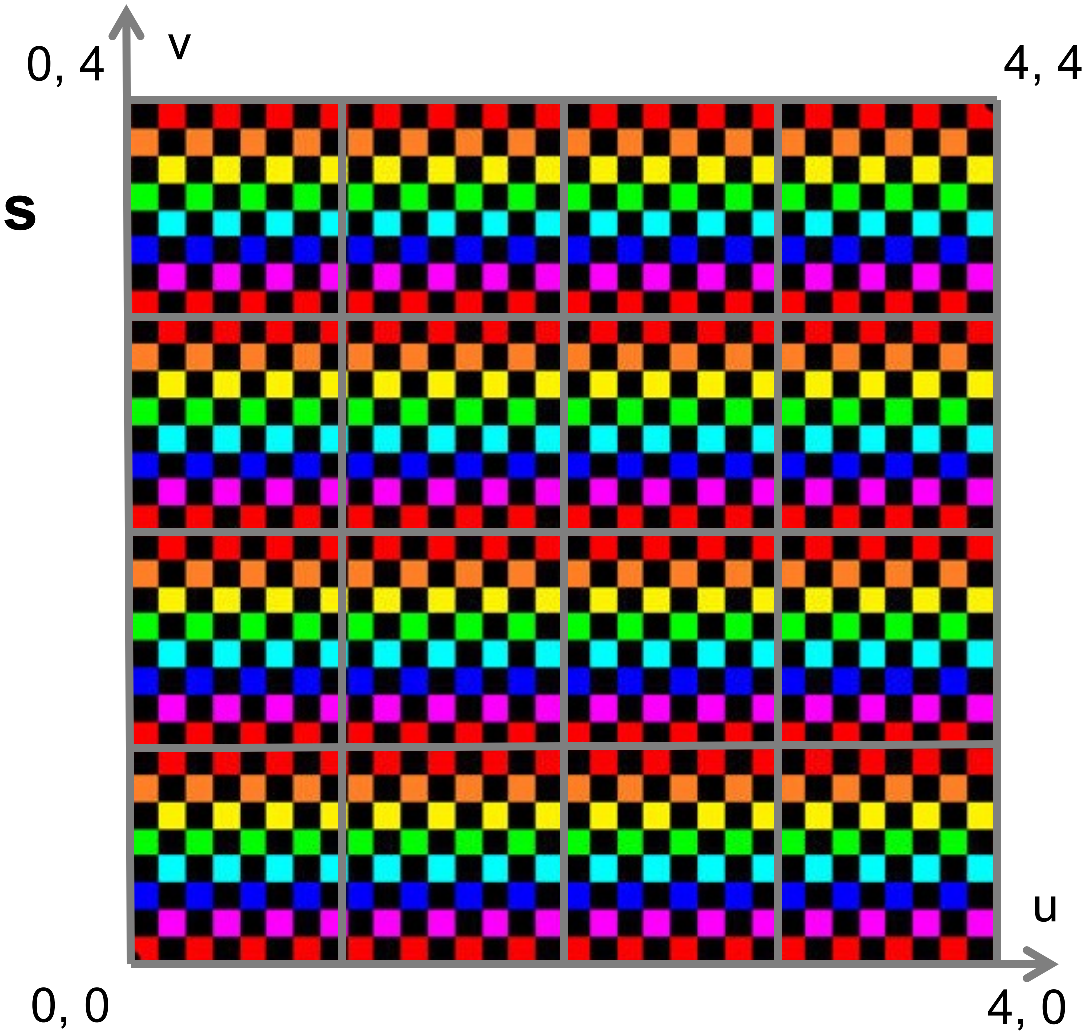
Wrap Mode

- **Texture Coordinates**
  - (u, v) in [0, 1] x [0, 1]
- **What if?**
  - (u, v) not in unit square?



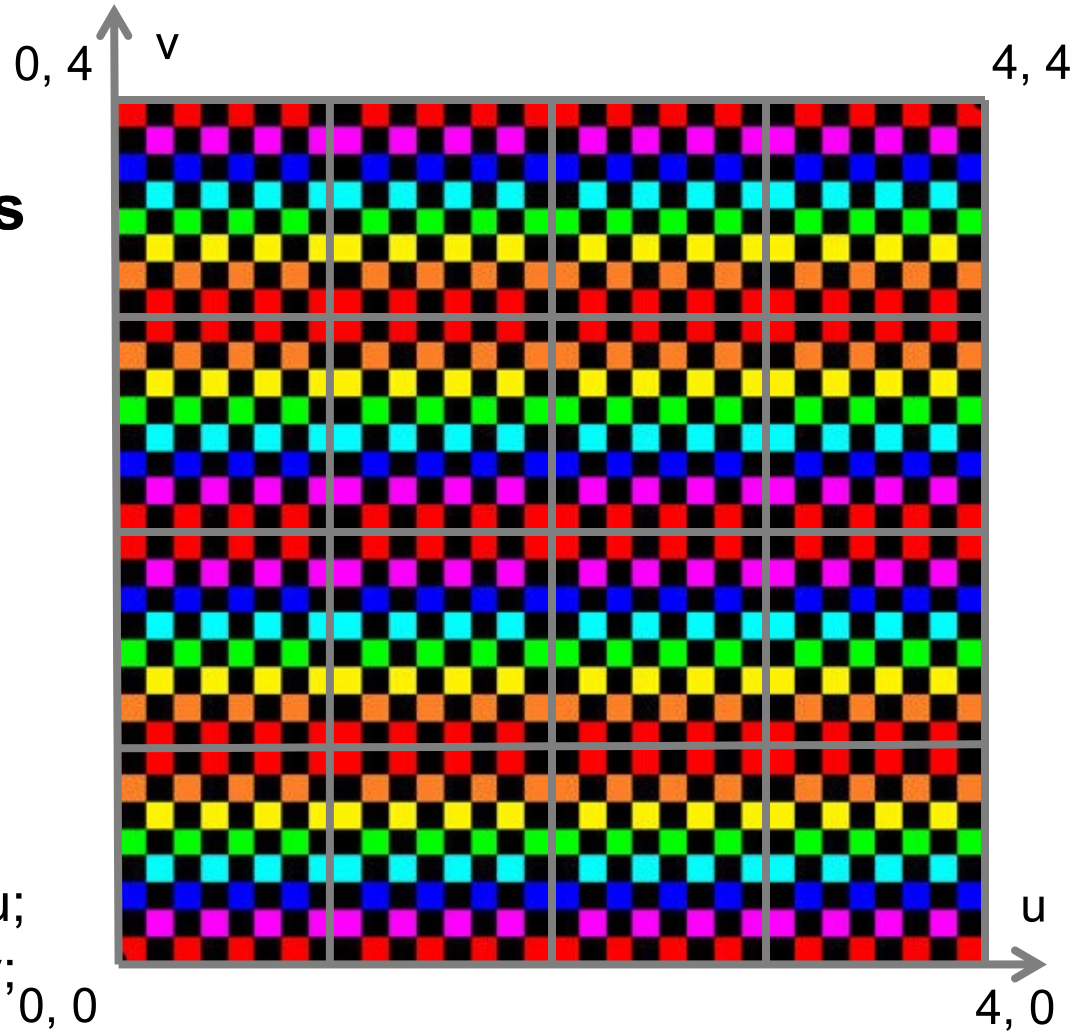
Wrap Mode

- **Repeat**
- **Fractional Coordinates**
  - tu = u - $\lfloor u \rfloor$;
  - tv = v - $\lfloor v \rfloor$;



Wrap Mode

- **Mirror**
- **Fractional Coordinates**
  - tu = u - └ u ┘;
  - tv = v - └ v ┘;
- **Lattice Coordinates**
  - lu = └ u ┘;
  - lv = └ v ┘;
- **Mirror if Odd**
  - if (lu % 2 == 1) tu = 1 – tu;
  - if (lv % 2 == 1) tv = 1 – tv;

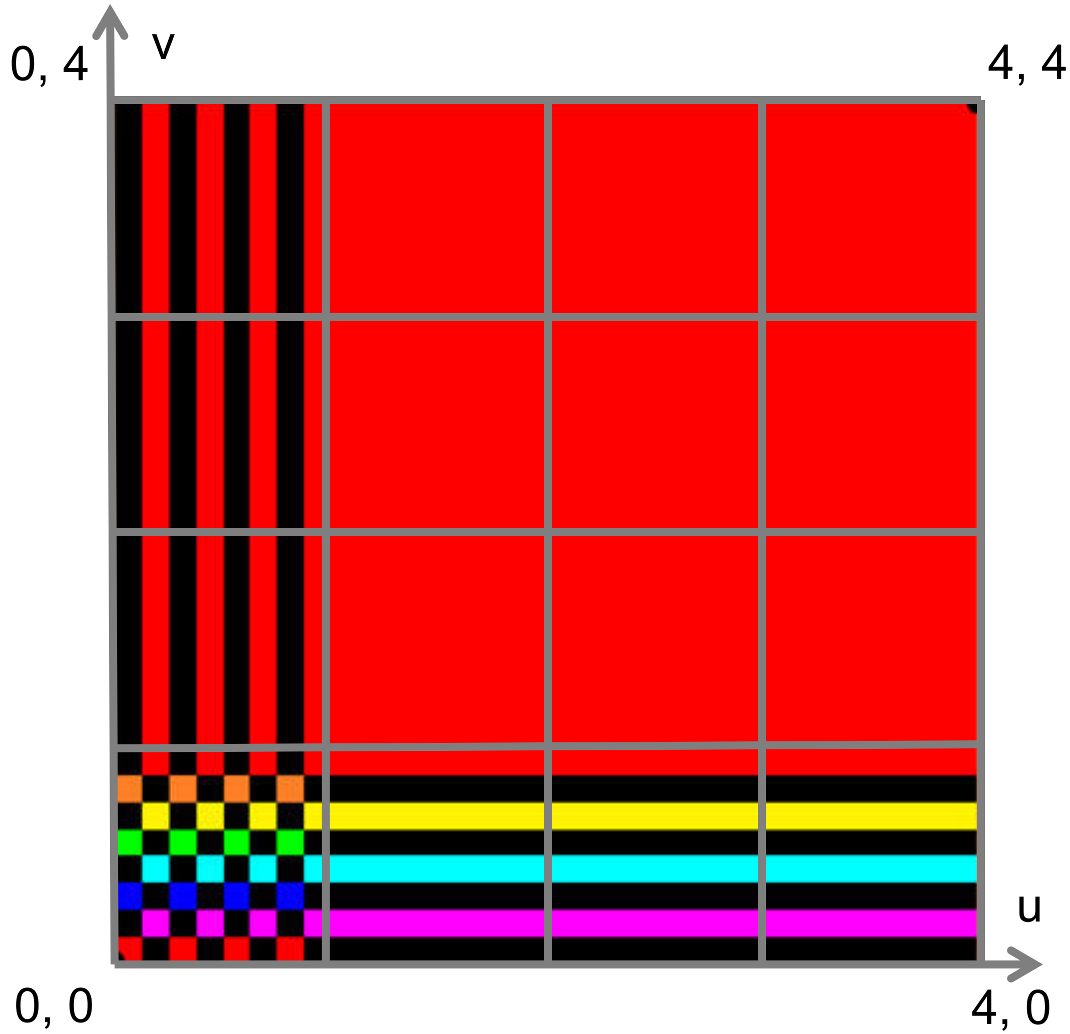


Wrap Mode

- **Clamp**

- **Clamp u to [0, 1]**
  - if (u < 0) tu = 0;
  - else if (u > 1) tu = 1;
  - else tu = u;

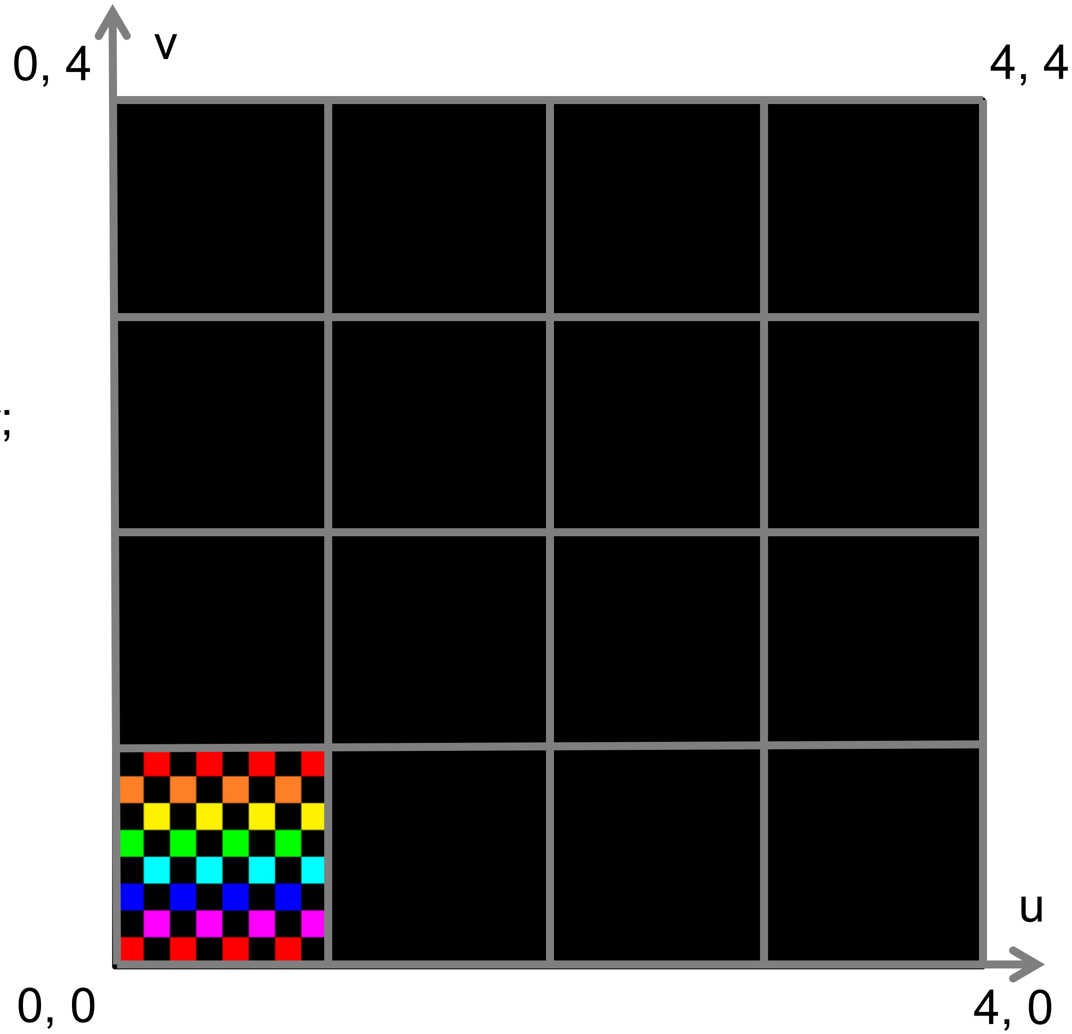
- **Clamp v to [0, 1]**
  - if (v < 0) tv = 0;
  - else if (v > 1) tv = 1;
  - else tv = v;



Wrap Mode

- **Border**

- **Check Bounds**
  - if (u < 0 || u > 1
    - || v < 0 || v > 1)
    - return backgroundColor;
  - else
    - tu = u;
    - tv = v;

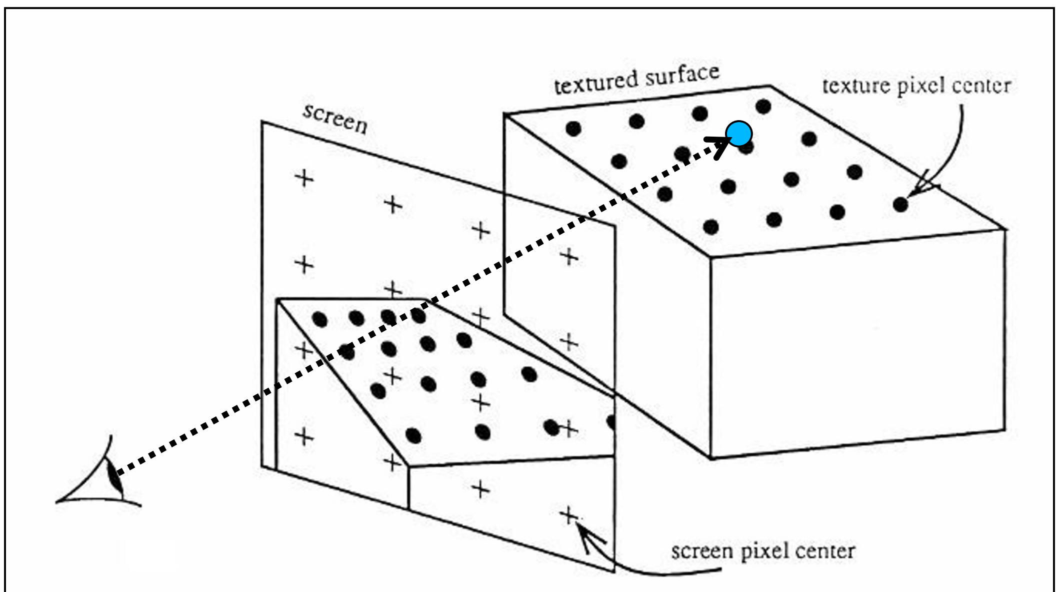


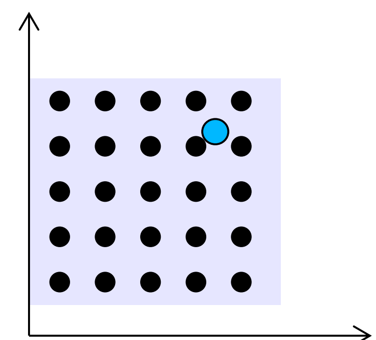
Wrap Mode

- **Comparison**

Reconstruction Filter

- **Image Texture**
  – Discrete set of sample values
- **In Practice**
  – Hit point generally does not exactly hit a texture sample
- **Reconstruct Continuous Function**
  – Use reconstruction filter to find color for hit point



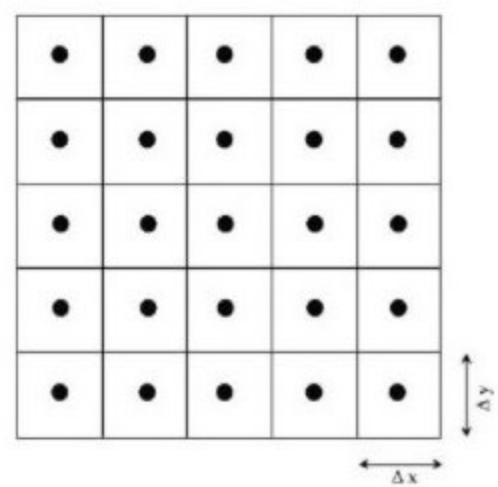


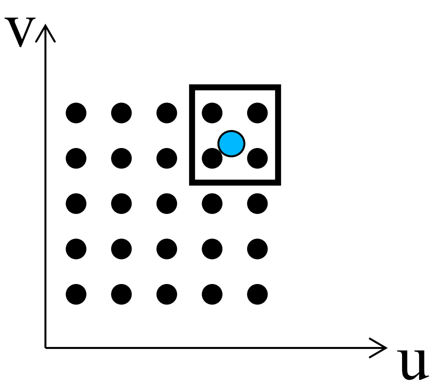
Texture Space

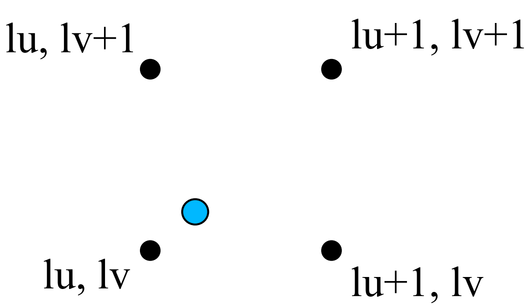
Nearest Neighbor

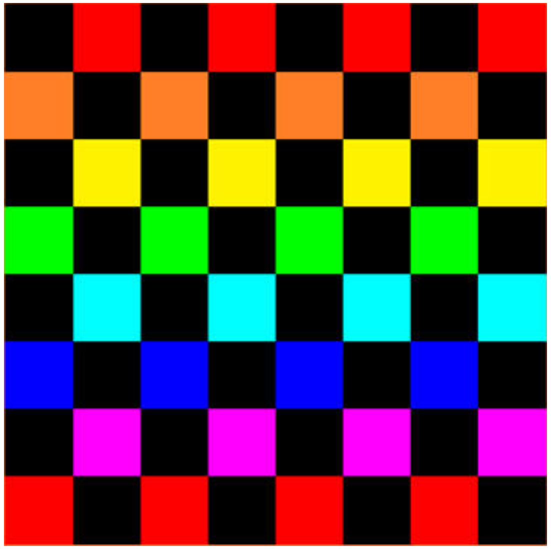
- **Local Coordinates**
  - Assuming cell-centered samples
  - u = tu * resU;
  - v = tv * resV;
- **Lattice Coordinates**
  - lu = min($\lfloor$ u $\rfloor$, resU – 1);
  - lv = min($\lfloor$ v $\rfloor$, resV – 1);
- **Texture Value**
  - return image[lu, lv];

Pixel centred registration



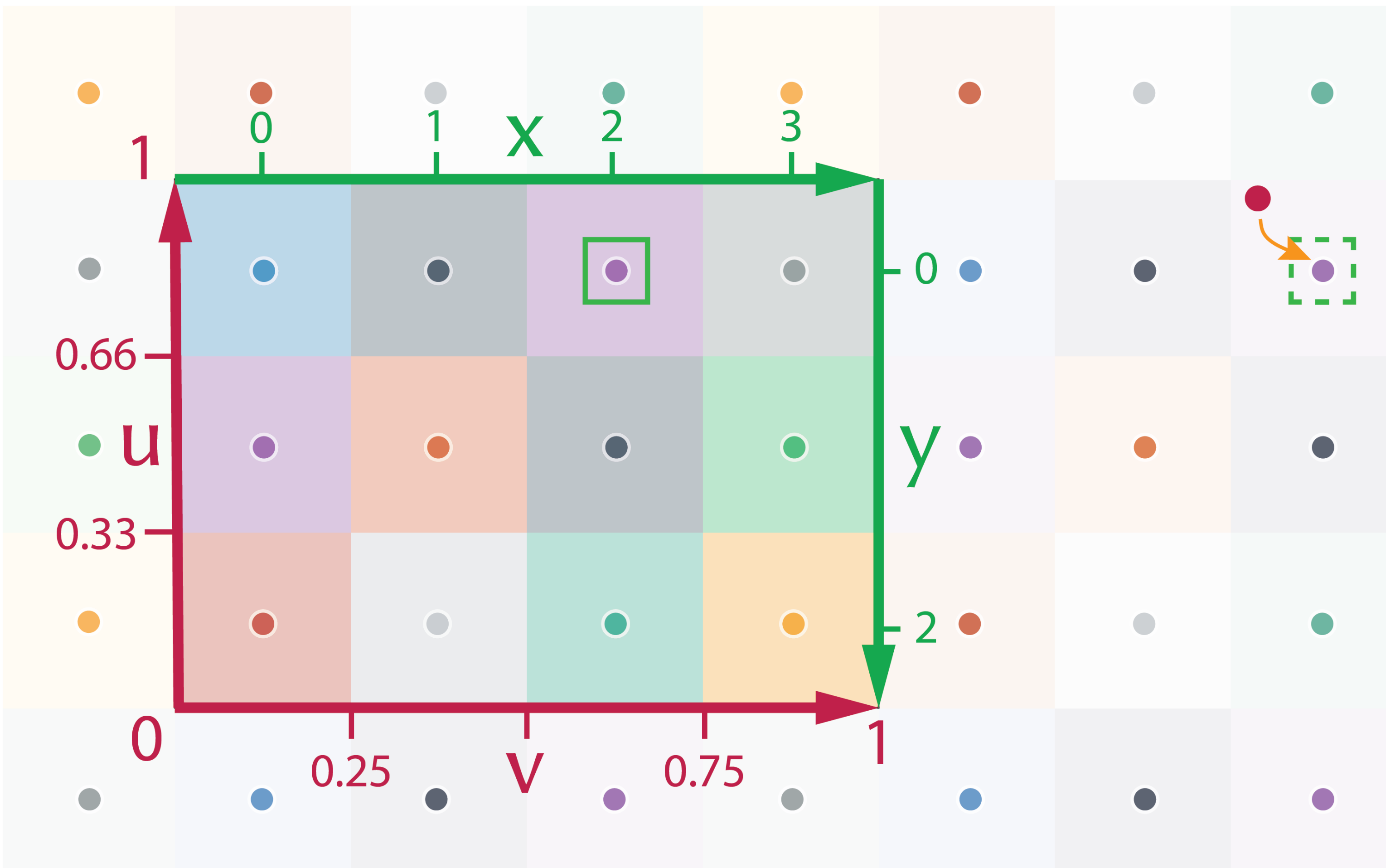






Nearest Neighbor

- **In Lightwave with Repeat Wrap Mode**

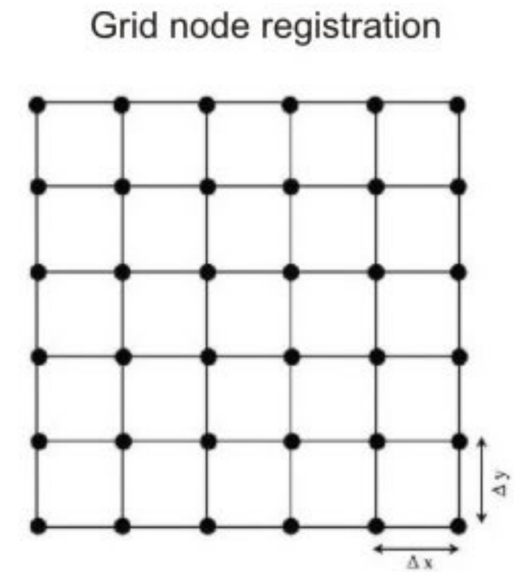


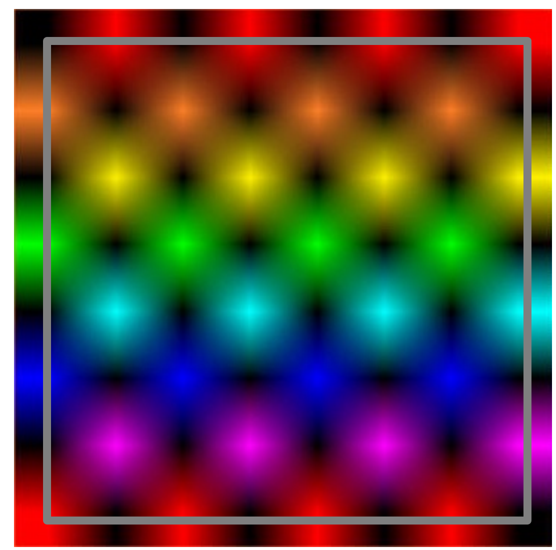
Bilinear Interpolation

- **Local Coordinates**
  - Assuming node-centered samples
  - u = tu * (resU – 1);
  - v = tv * (resV – 1);

- **Fractional Coordinates**
  - $fu = u - \lfloor u \rfloor$;
  - $fv = v - \lfloor v \rfloor$;

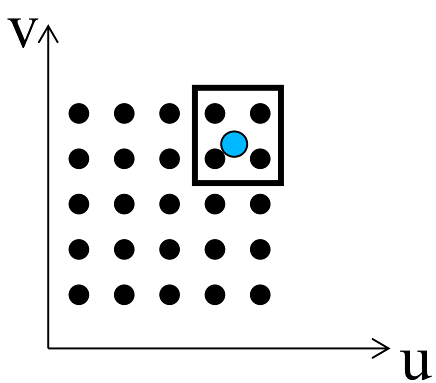
- **Texture Value**
  - $\text{return } (1-fu)\,(1-fv)\,\text{image}[\lfloor u \rfloor, \lfloor v \rfloor]$
    $+ (1-fu)\,(fv)\,\text{image}[\lfloor u \rfloor, \lfloor v \rfloor+1]$
    $+ (fu)\,(1-fv)\,\text{image}[\lfloor u \rfloor+1, \lfloor v \rfloor]$
    $+ (fu)\,(fv)\,\text{image}[\lfloor u \rfloor+1, \lfloor v \rfloor+1]$

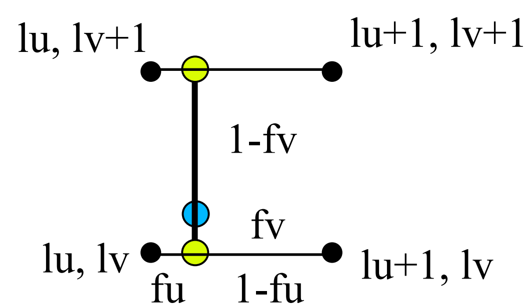




Bilinear Interpolation

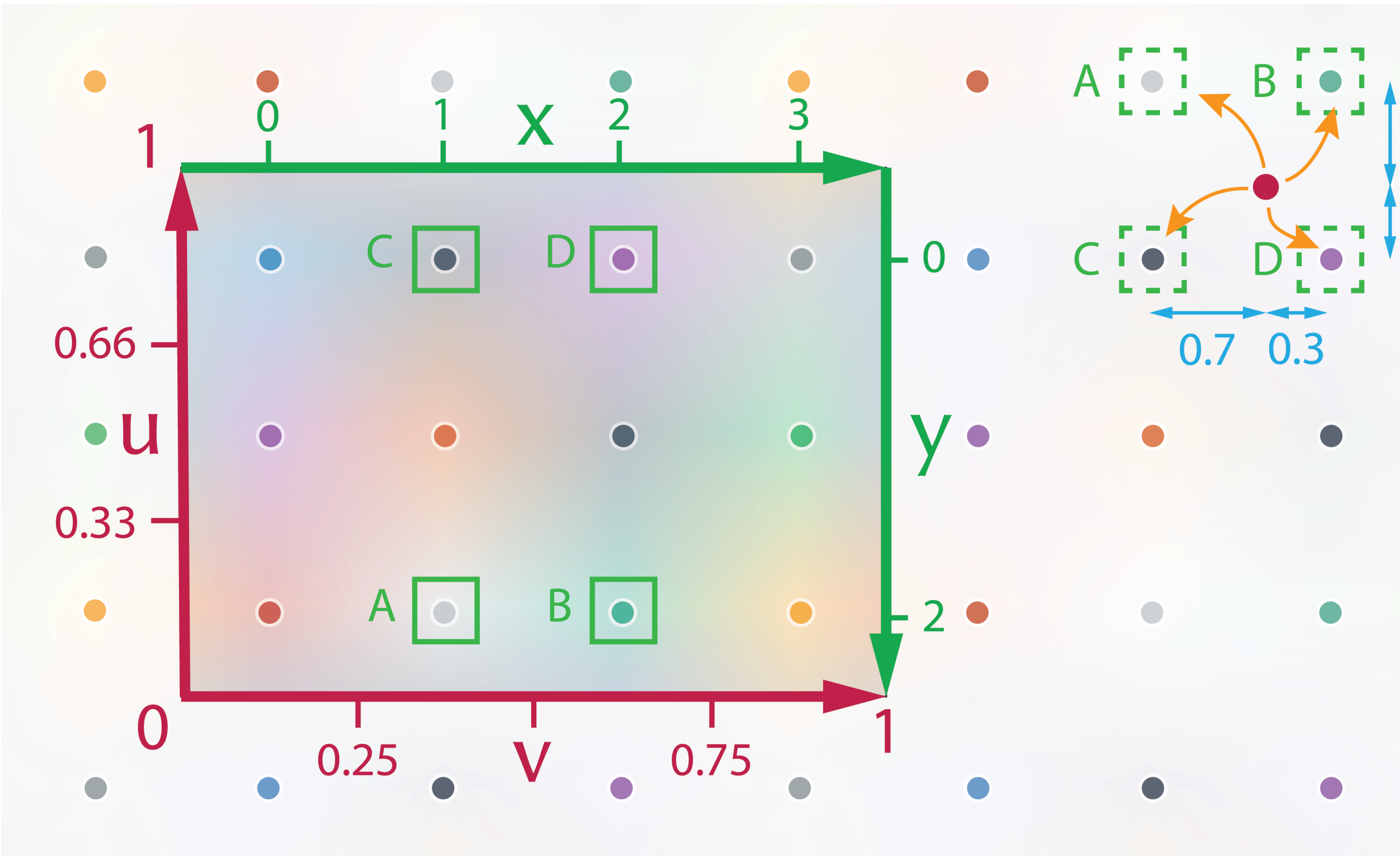
- **Successive Linear Interpolations**
  - u0 = (1-fv) image[$\lfloor u \rfloor$, $\lfloor v \rfloor$]
    + (fv) image[$\lfloor u \rfloor$, $\lfloor v \rfloor$+1];
  - u1= (1-fv) image[$\lfloor u \rfloor$+1, $\lfloor v \rfloor$]
    + (fv) image[$\lfloor u \rfloor$+1, $\lfloor v \rfloor$+1];
  - return (1-fu) u0
    + (fu) u1;





Bilinear Interpolation

- **In Lightwave with Repeat Wrap Mode**



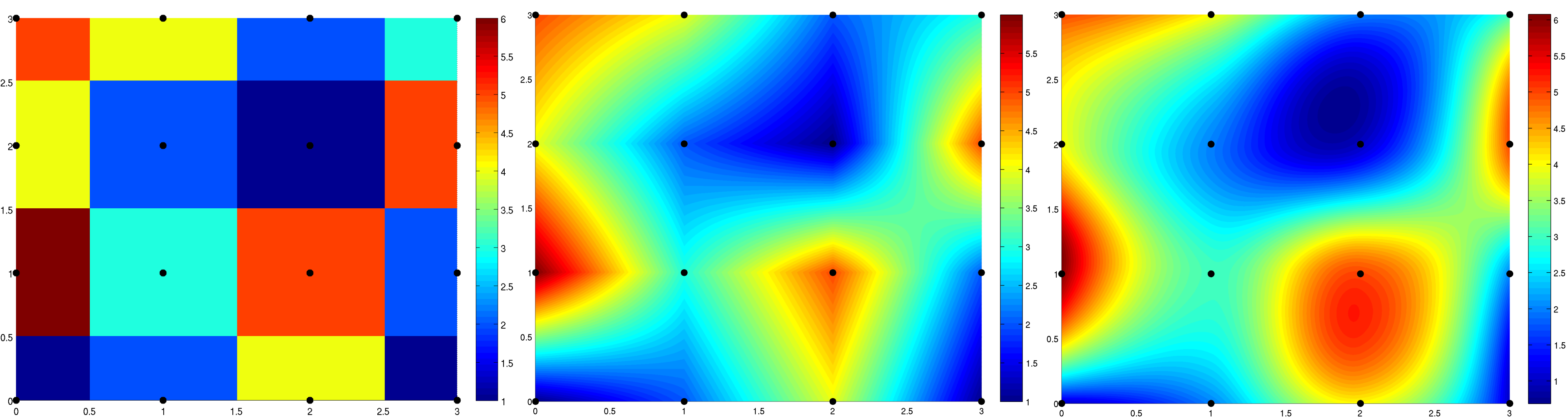
Nearest vs. Bilinear Interpolation


GL_NEAREST


GL_LINEAR

Bicubic Interpolation

- **Properties**
  - Assuming node-centered samples
  - Essentially based on cubic splines (see later)
- **Pros**
  - Even smoother
- **Cons**
  - More complex & expensive (4x4 kernel)
  - Overshoot



Discussion: Image Textures

- **Pros**
  - Simple generation
    - Painted, simulation, ...
  - Simple acquisition
    - Photos, videos

- **Cons**
  - Illumination “frozen” during acquisition (e.g. photo)
  - Limited resolution
  - Susceptible to aliasing
  - High memory requirements (often HUGE for films, 100s of GB)
  - Issues when mapping 2D image onto 3D object

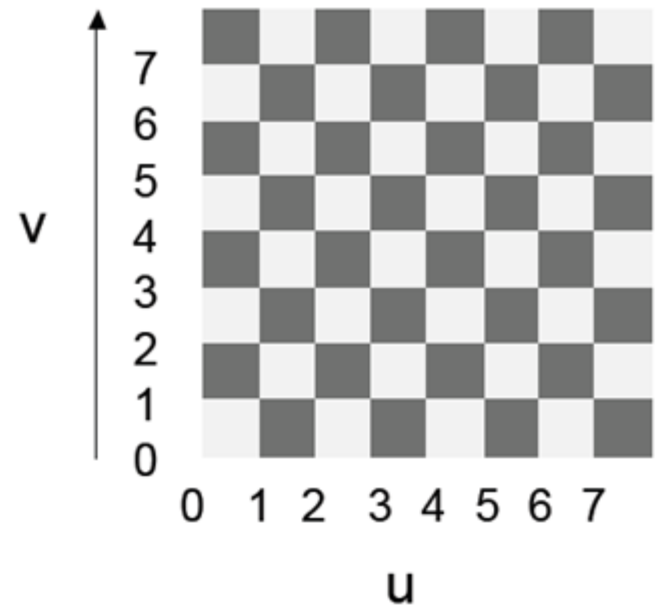
PROCEDURAL TEXTURES

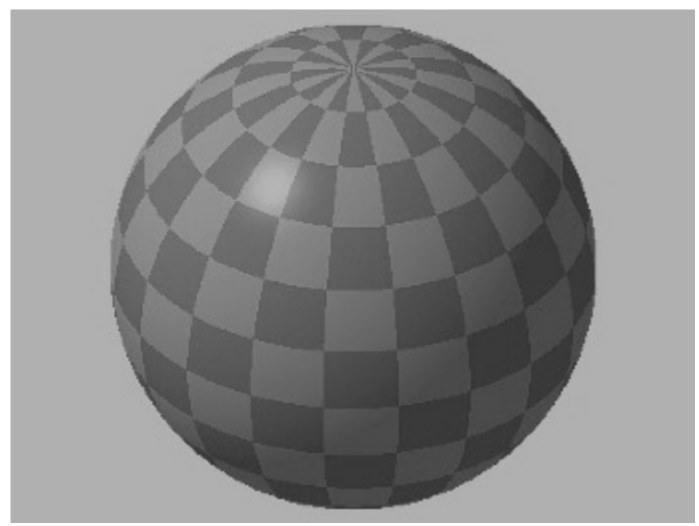
Discussion

- **Cons**
  - Possibly non-trivial programming
- **Pros**
  - Flexibility & parametric control
  - Unlimited resolution
  - Anti-aliasing possible
  - Low memory requirements
  - May be directly defined as 3D “image” mapped to 3D geometry
  - Low-cost visual complexity

2D Checkerboard

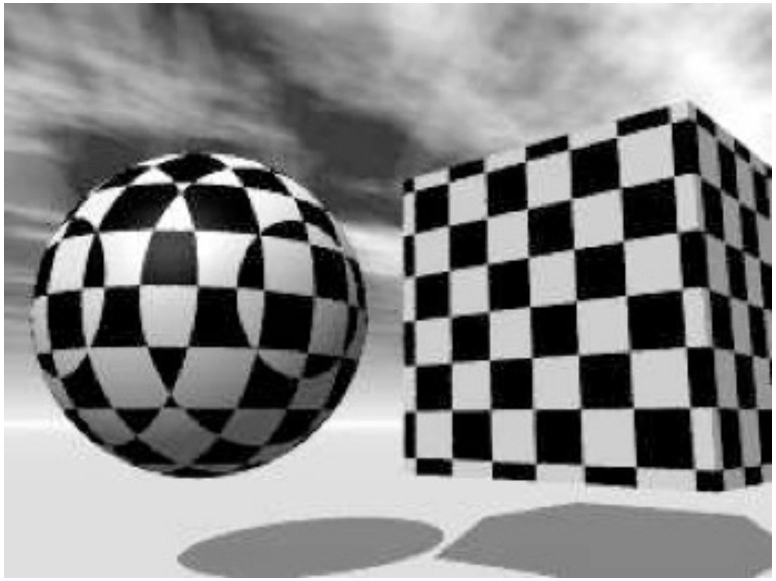
- **Lattice Coordinates**
  - lu = $\lfloor u \rfloor$
  - lv = $\lfloor v \rfloor$
- **Compute Parity**
  - parity = (lu + lv) % 2;
- **Return Color**
  - if (parity == 1)
    - return color1;
  - else
    - return color0;

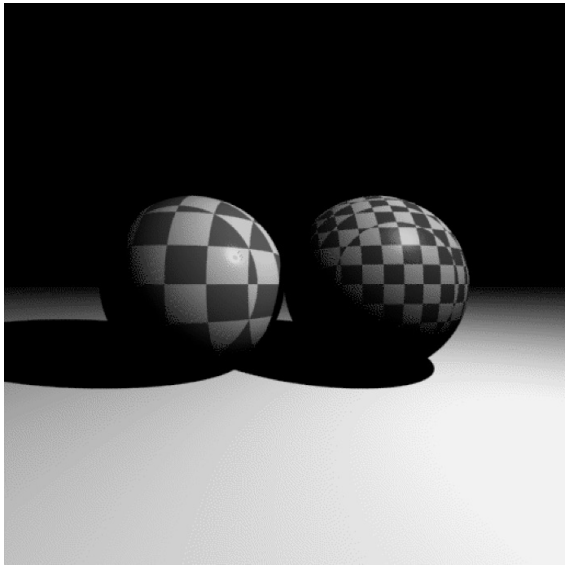




3D Checkerboard - Solid Texture

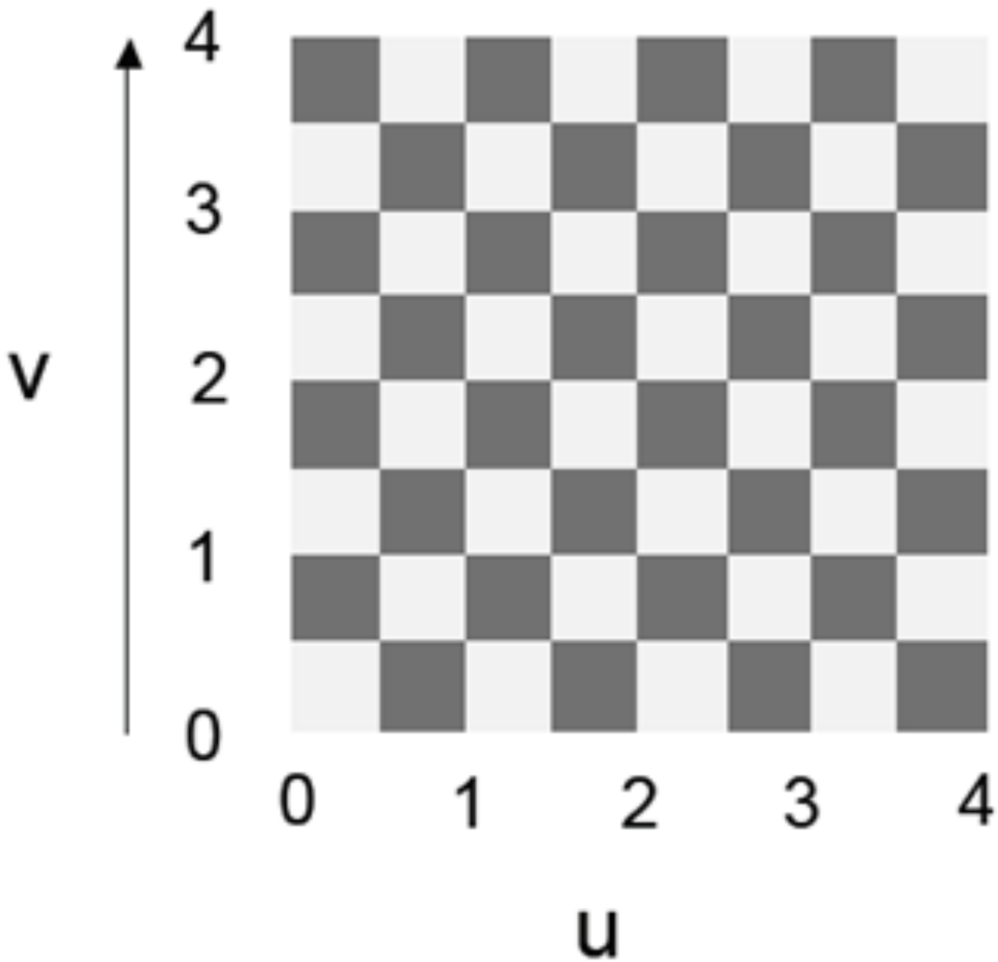
- **Lattice Coordinates**
  - $lu = \lfloor u \rfloor$
  - $lv = \lfloor v \rfloor$
  - $lw = \lfloor w \rfloor$
- **Compute Parity**
  - parity = (lu + lv + lw) % 2;
- **Return Color**
  - if (parity == 1)
    - return color1;
  - else
    - return color0;





2D Checkerboard – Nearest-Node

- **Fractional Coordinates**
  - $fu = u - \lfloor u \rfloor$
  - $fv = v - \lfloor v \rfloor$
- **Compute Booleans**
  - bu = fu < 1/2;
  - bv = fv < 1/2;
- **Return Color**
  - if (bu ^ bv)
    - return color1;
  - else
    - return color0;

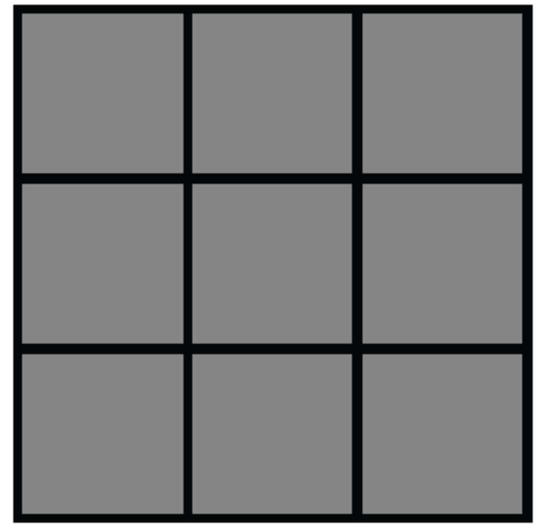


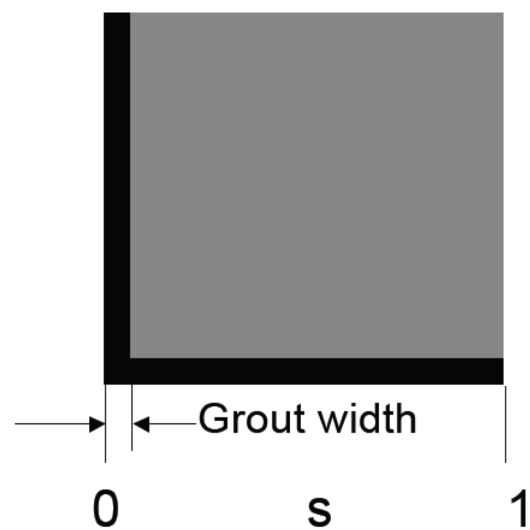
Tile

- **Fractional Coordinates**
  - $fu = u - \lfloor u \rfloor$
  - $fv = v - \lfloor v \rfloor$

- **Compute Booleans**
  - bu = fu < groutWidth;
  - bv = fv < groutWidth;

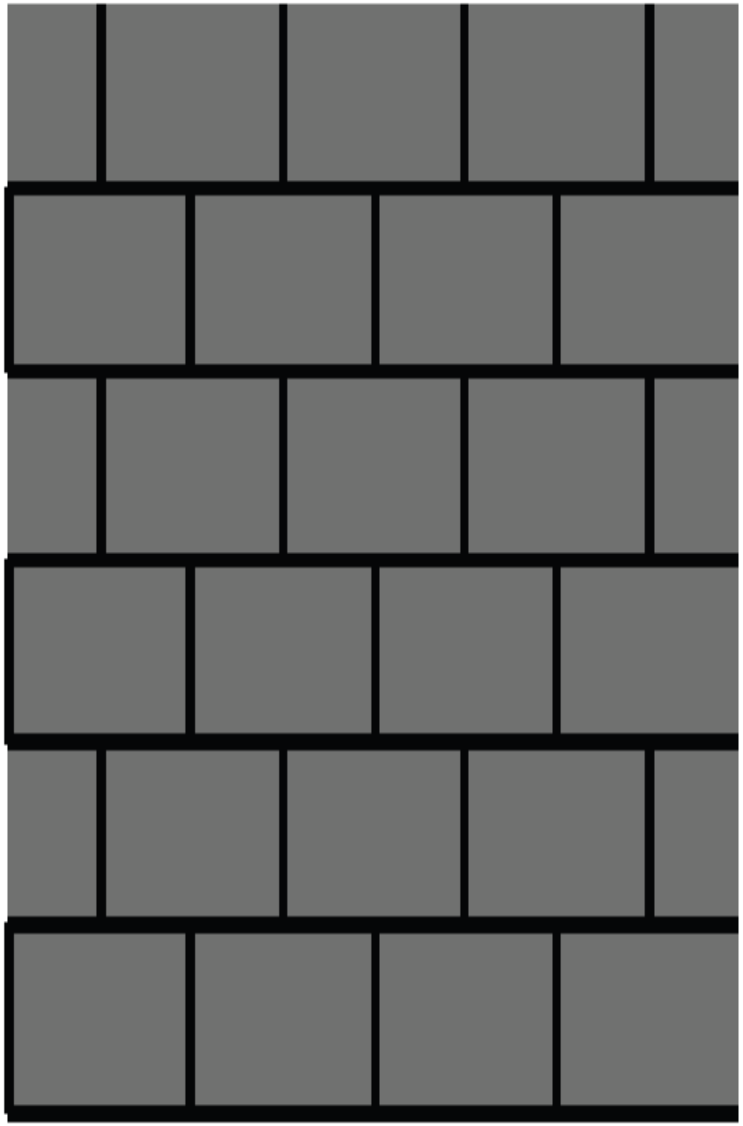
- **Return Color**
  - if (bu || bv)
    - return groutColor;
  - else
    - return tileColor;



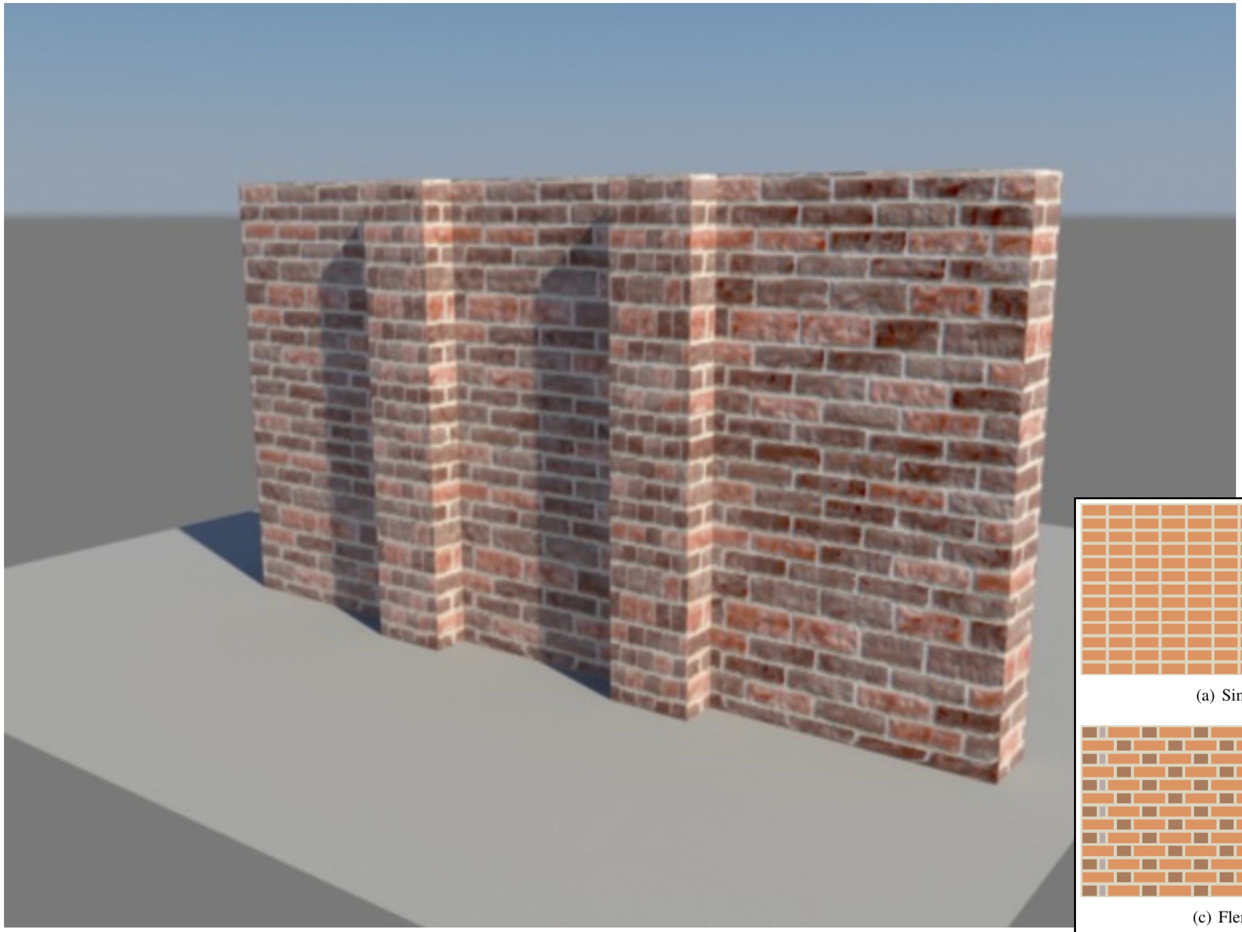


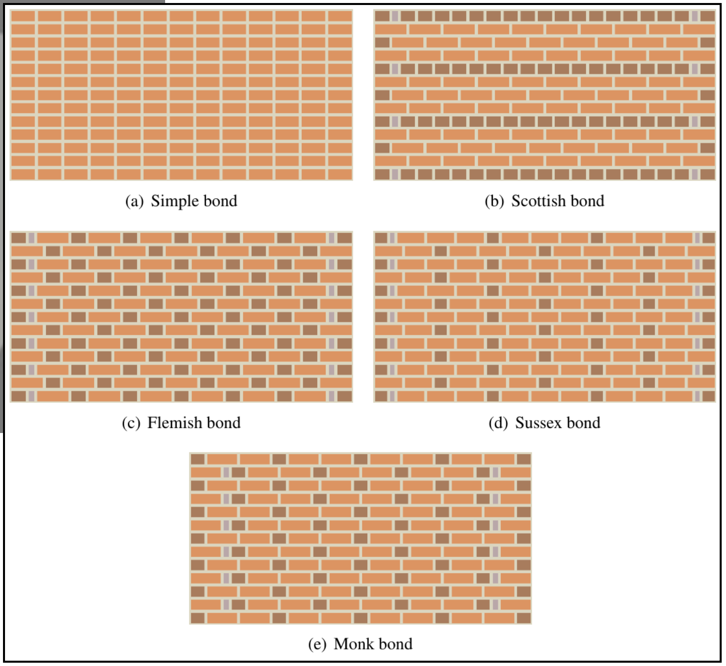
Brick

- **Shift Column for Odd Rows**
  - parity = $\lfloor v \rfloor$ % 2;
  - u -= parity * 0.5;
- **Fractional Coordinates**
  - fu = u - $\lfloor u \rfloor$
  - fv = v - $\lfloor v \rfloor$
- **Compute Booleans**
  - bu = fu < mortarWidth;
  - bv = fv < mortarWidth;
- **Return Color**
  - if (bu || bv)
    - return mortarColor;
  - else
    - return brickColor;



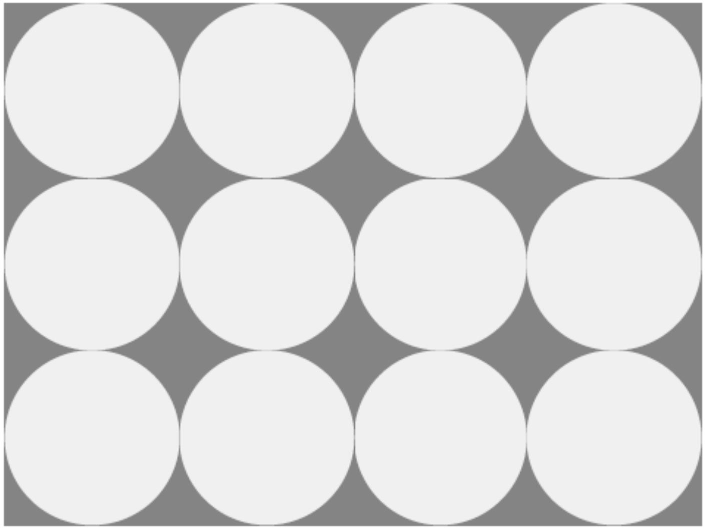
More Variation



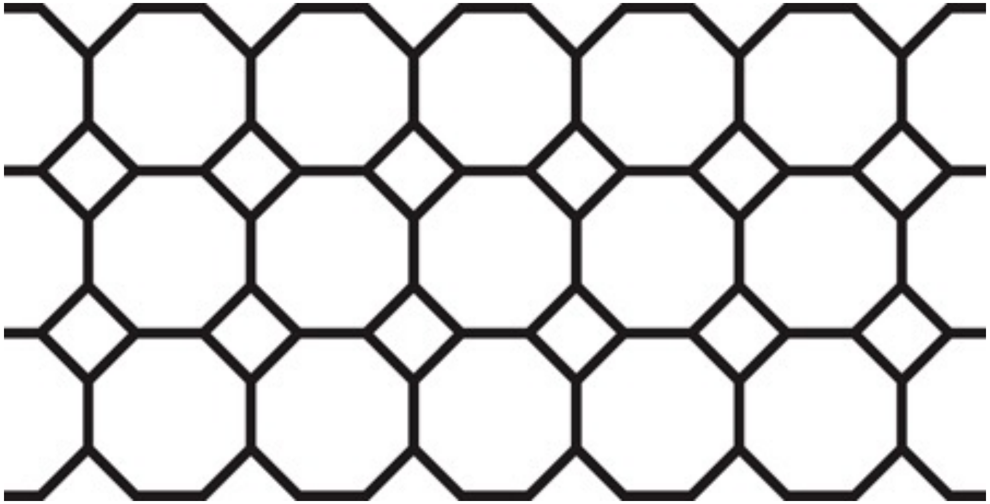


Other Patterns

- **Circular Tiles**



- **Octagonal Tiles**



- **Use your imagination!**

Perlin Noise

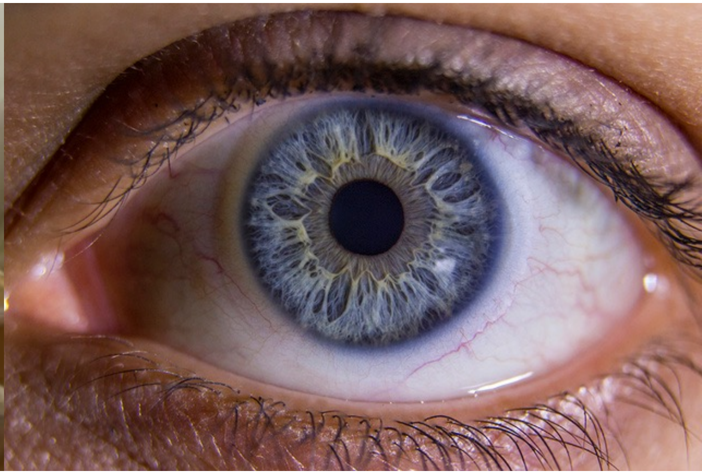
- **Natural Patterns**
  - Similarity between patches at different locations
    - Repetitiveness, coherence (e.g. skin of a tiger or zebra)
  - Similarity on different resolution scales
    - Self-similarity
  - But never completely identical
    - Additional disturbances, turbulence, noise

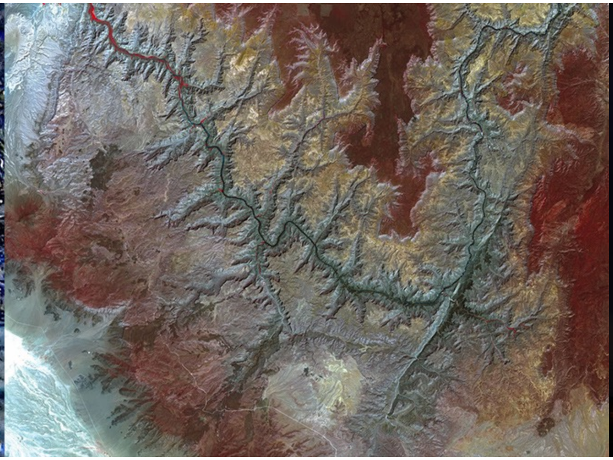
- **Mimic Statistical Properties**
  - Purely empirical approach
  - Looks convincing, but has nothing to do with material's physics

Perlin Noise

- **Natural Fractals**

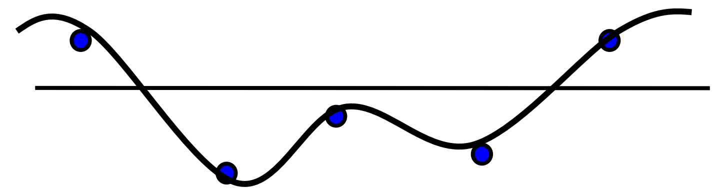




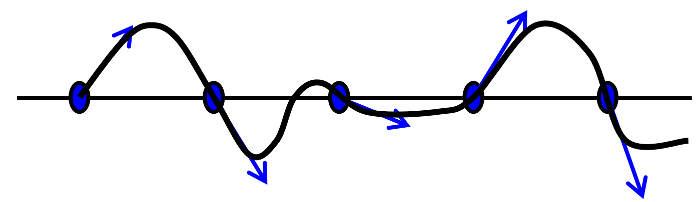


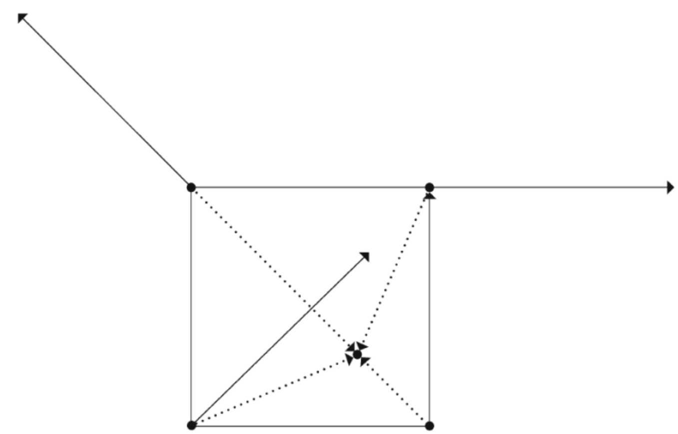

Noise Function

- **Noise(x, y, z)**
  - Statistical invariance under rotation
  - Statistical invariance under translation
  - Roughly fixed frequency of ~1 Hz



- **Integer Lattice (i, j, k)**
  - Value noise
    - Random value at lattice points
  - Gradient noise
    - Random gradient vector at lattice point
    - Compute lattice values as dot products
  - Interpolation
    - Bi-/tri-linear or cubic (Hermite spline)
  - Hash function
    - Randomized look up
    - Virtually infinite extent

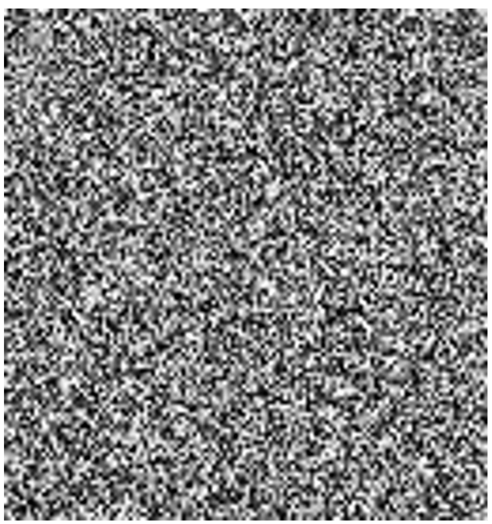




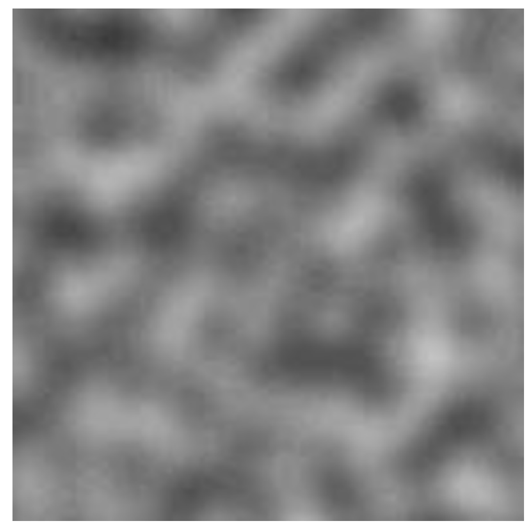
Noise vs. Noise

- **Value Noise vs. Gradient Noise**
  - Gradient noise has lower regularity artifacts
  - More high frequencies in noise spectrum

- **Random Values vs. Perlin Noise**
  - Stochastic vs. deterministic



Random values
at each pixel

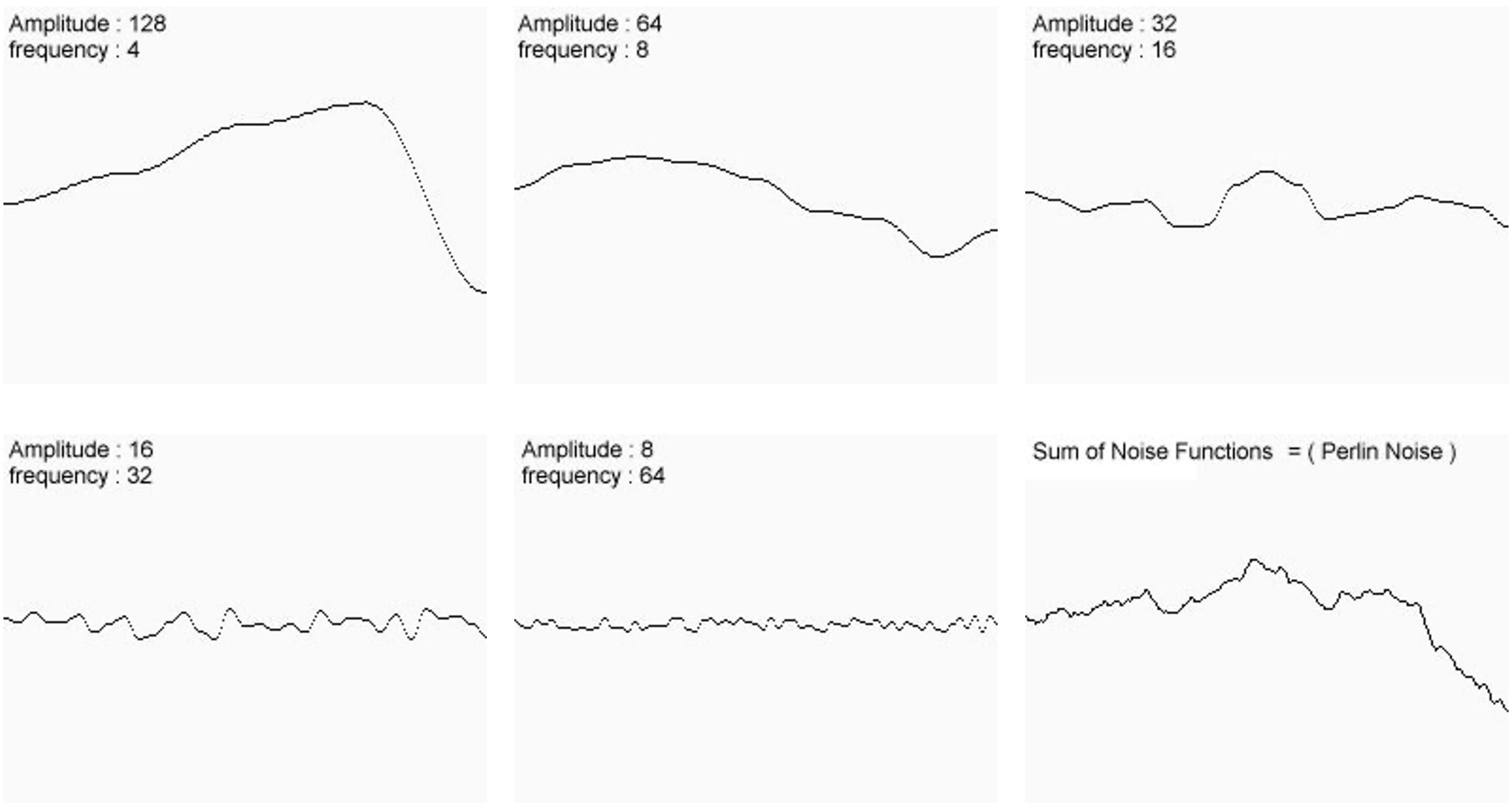


Gradient noise

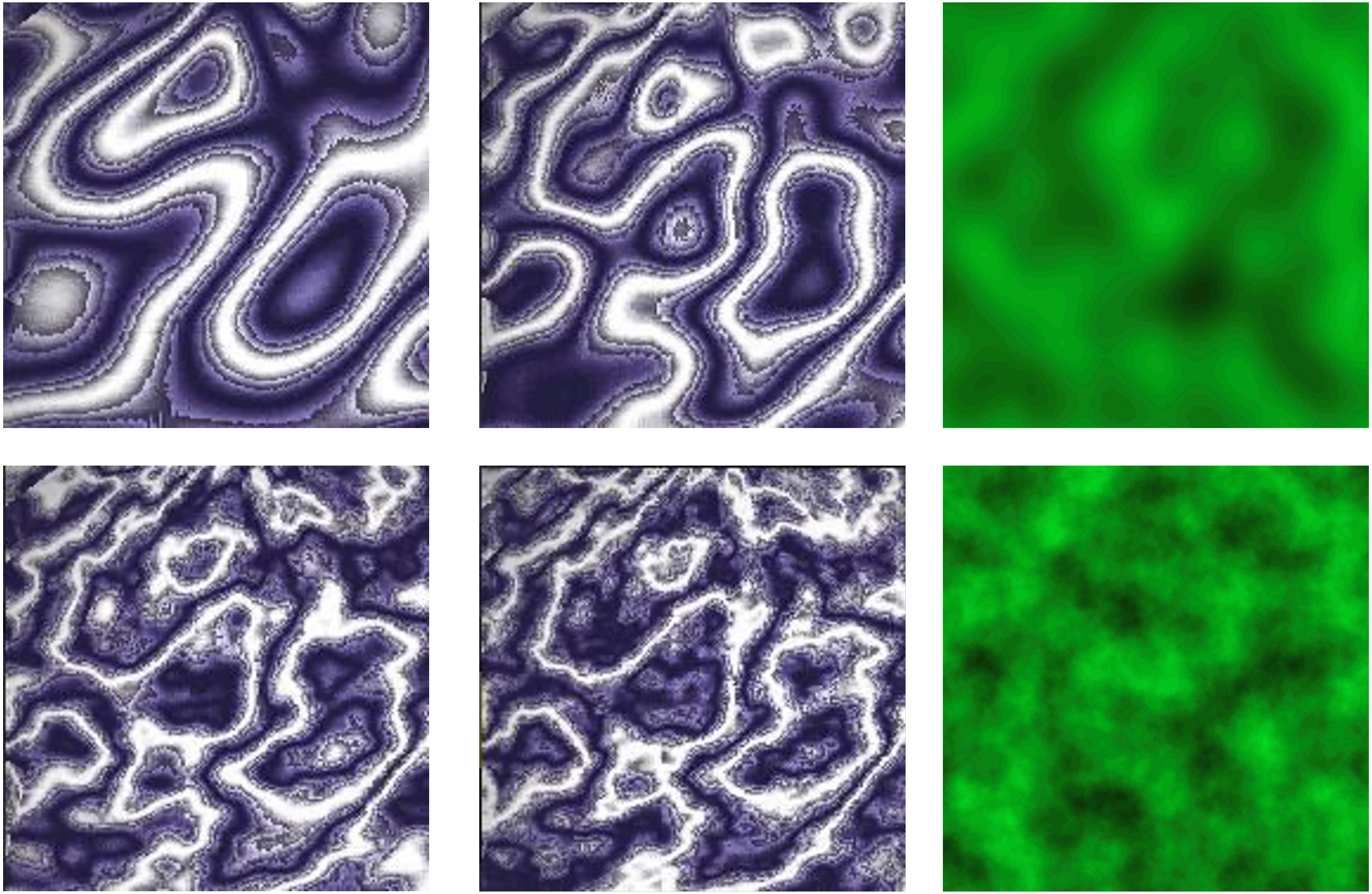
Turbulence Function

- **Noise Function**
  - Single spike in frequency spectrum
- **Natural Textures**
  - Decreasing amplitude for 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*
    - Power spectrum : $a_i = 1 \, / \, f_i$
    - Brownian motion: $a_i = 1 \, / \, f_i^2$
  - Summation truncation
    - 1st term: noise(x)
    - 2nd term: noise(2x)/2
    - …
    - Until period $(1/f_k)$ < 2 pixel-size (band limit)

Synthesis of Turbulence (1-D)

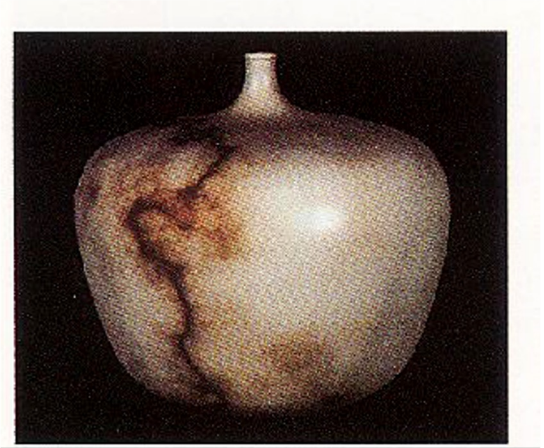


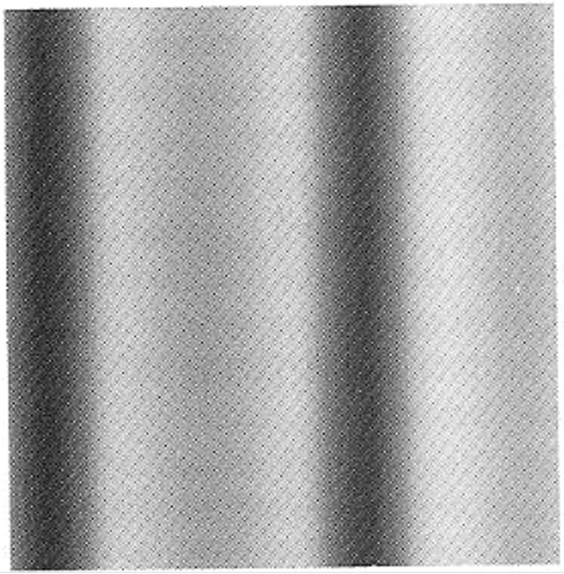
Synthesis of Turbulence (2-D)



Example: Marble

- **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)))





Solid Noise

- **3D Noise Texture**
  - Wood
  - Bump map
  - Marble

Others Applications

- **Bark**
  - Turbulated saw-tooth function

- **Clouds**
  - White blobs
  - Turbulated transparency along edge

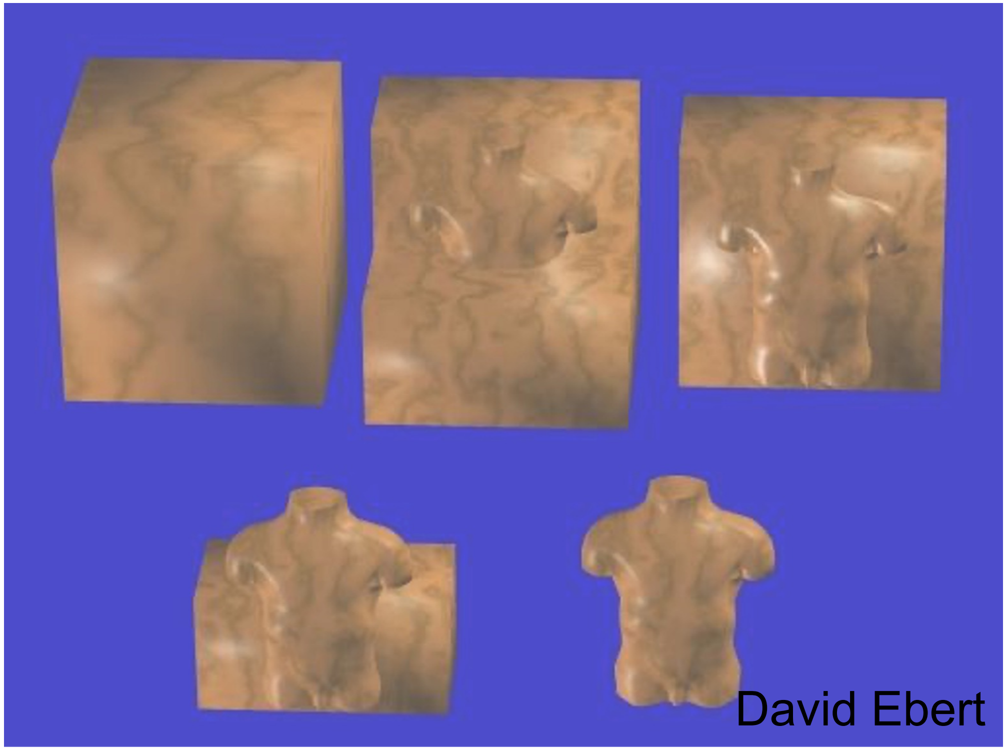
- **Animation**
  - Vary procedural texture function’s parameters over time

- **See Rainforest ShaderToy**

TEXTURE MAPPING

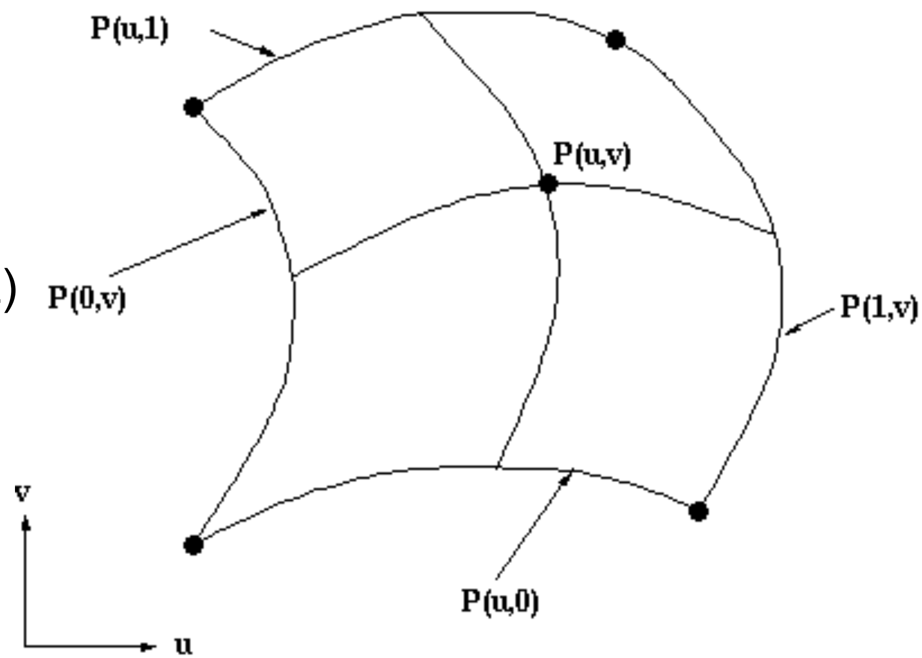
Textures Coordinates

- **Solid Textures**
  - 3D world/object (x,y,z) coords → 3D (u,v,w) texture coordinates
  - Similar to carving object out of material block
- **2D Textures**
  - 3D Cartesian (x,y,z) coordinates → 2D (u,v) texture coordinates?



Parametric Surfaces

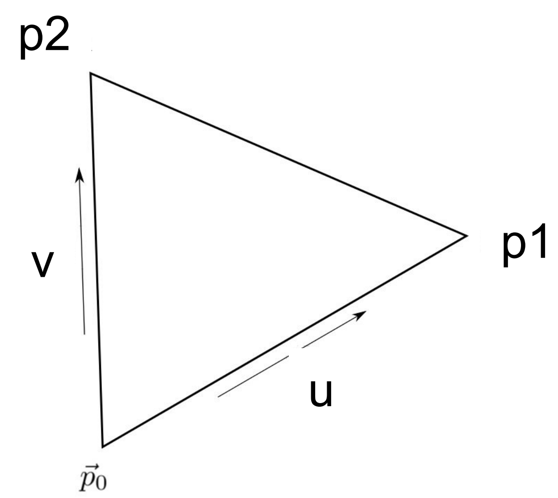
- **Definition**
  - Surface defined by parametric function
    - (x, y, z) = p(u, v)
  - Input
    - Parametric coordinates: (u, v)
  - Output
    - Cartsesian coordinates: (x, y, z)

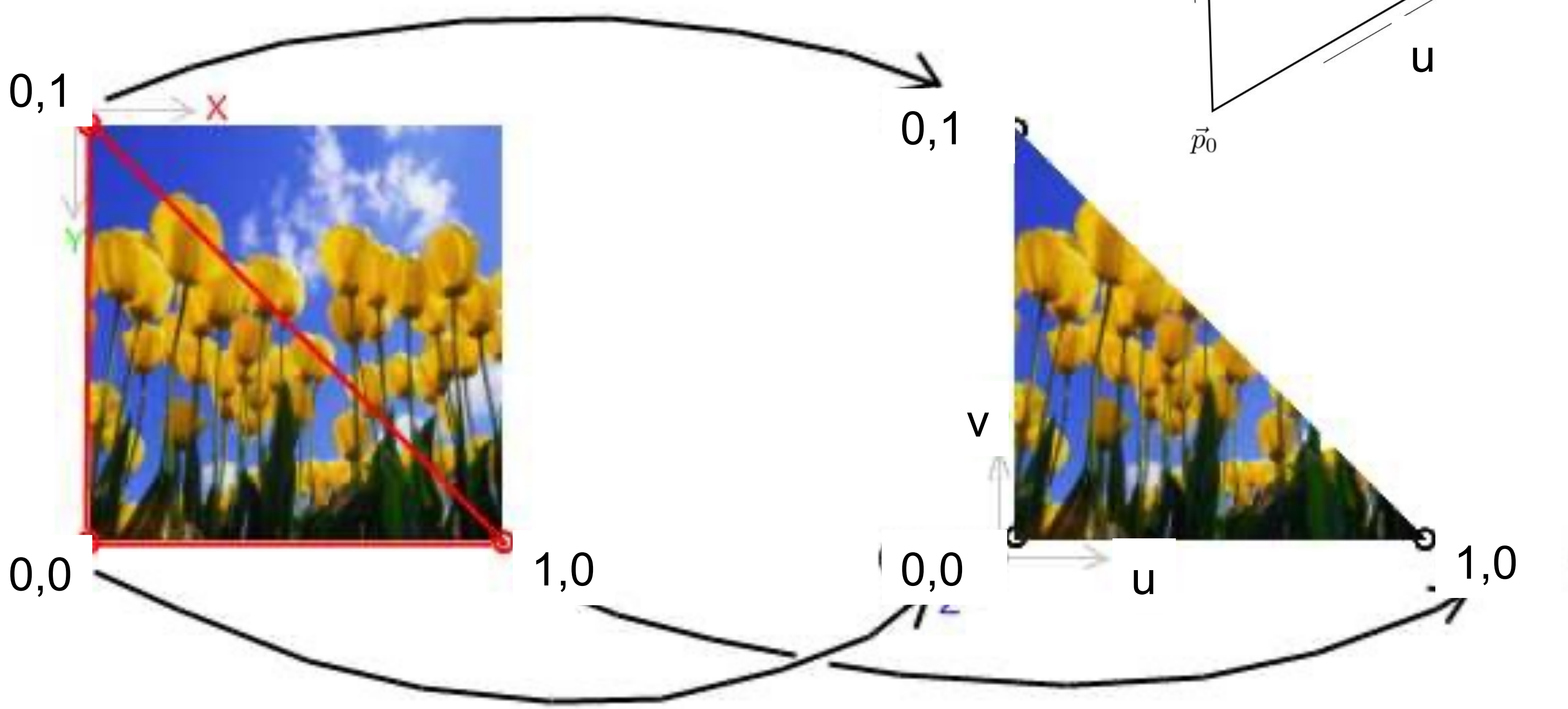


- **Texture Coordinates**
  - Directly derived from surface parameterization
  - Invert parametric function
    - From world coordinates to parametric coordinates

Parametric Surfaces

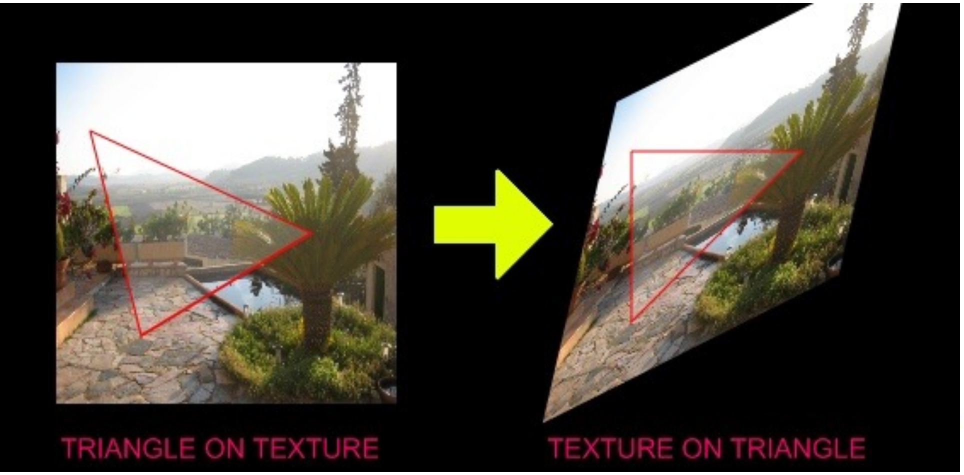
- **Triangle**
  - Use barycentric coordinates directly
  - $p(u,v) = (1 - u - v)p_0 + up_1 + v\,p_2$

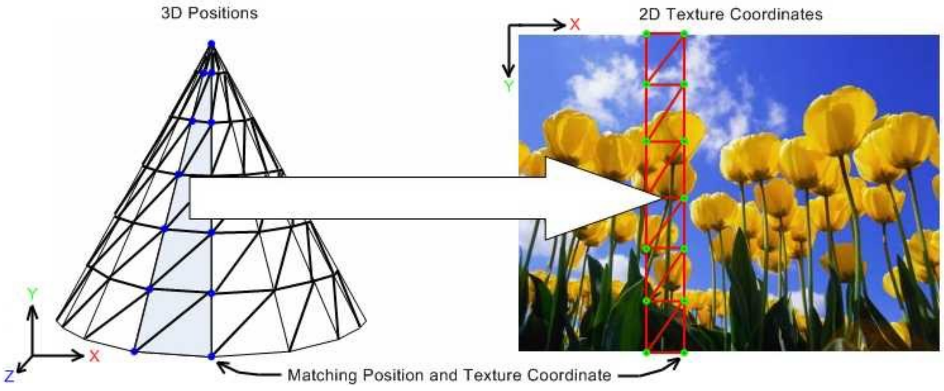




Parametric Surfaces

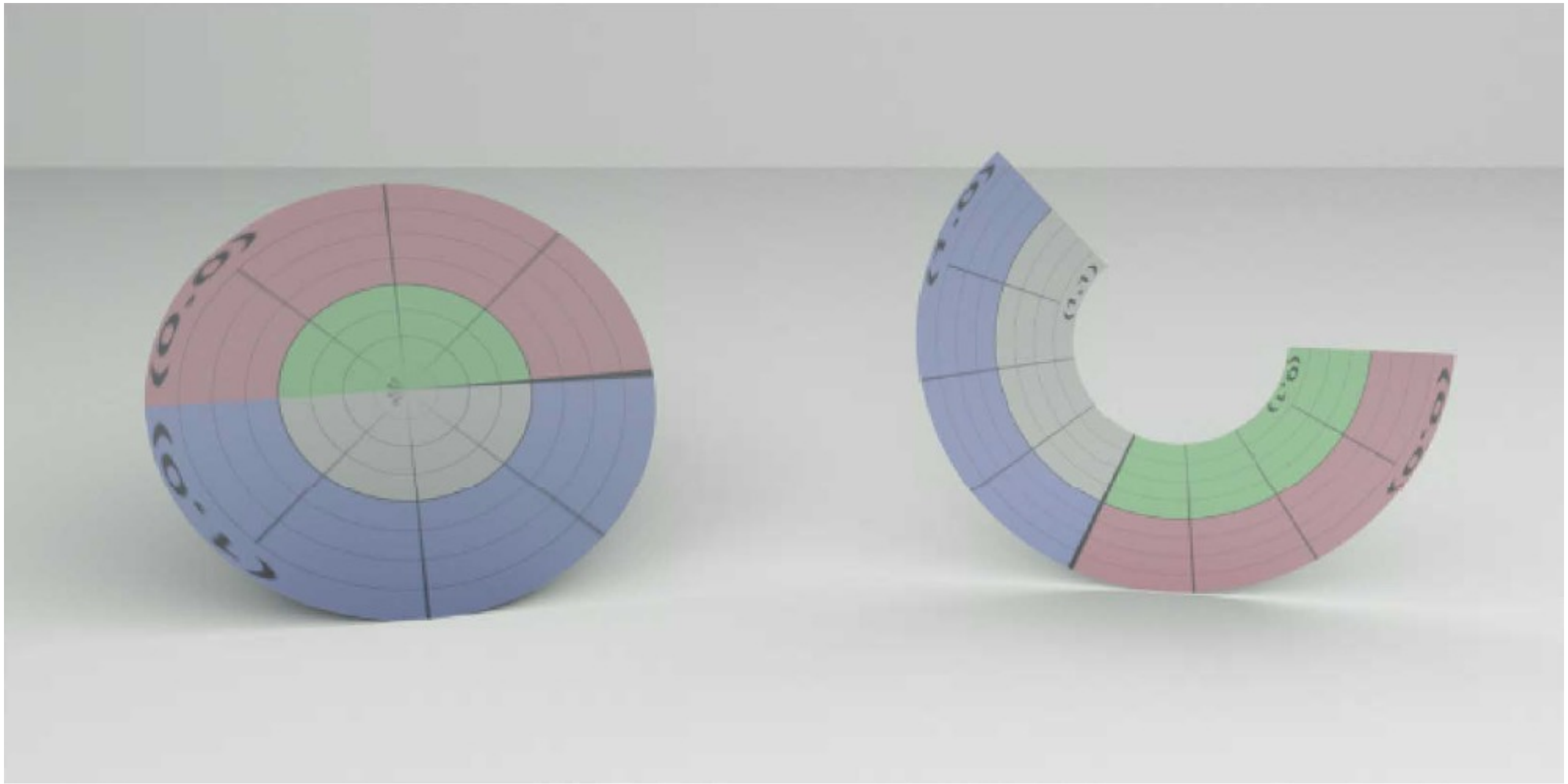
- **Triangle Mesh**
  - Associate a predefined texture coordinate to each triangle vertex
    - Interpolate texture coordinates using barycentric coordinates
    - $u = \lambda_0 p_{0u} + \lambda_1 p_{1u} + \lambda_2 p_{2u}$
    - $v = \lambda_0 p_{0v} + \lambda_1 p_{1v} + \lambda_2 p_{2v}$
  - Texture mapped onto manifold
    - Single texture shared by many triangles



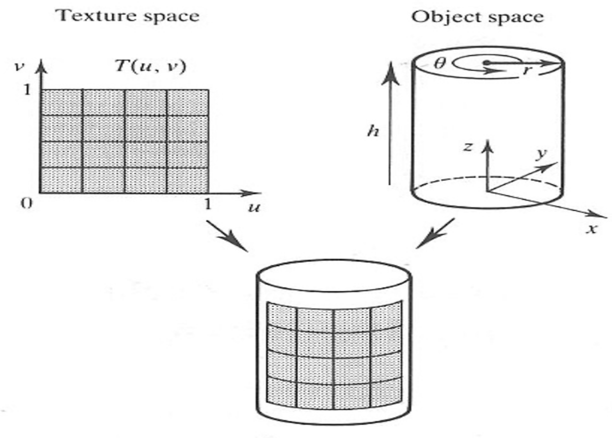


Parametric Surfaces

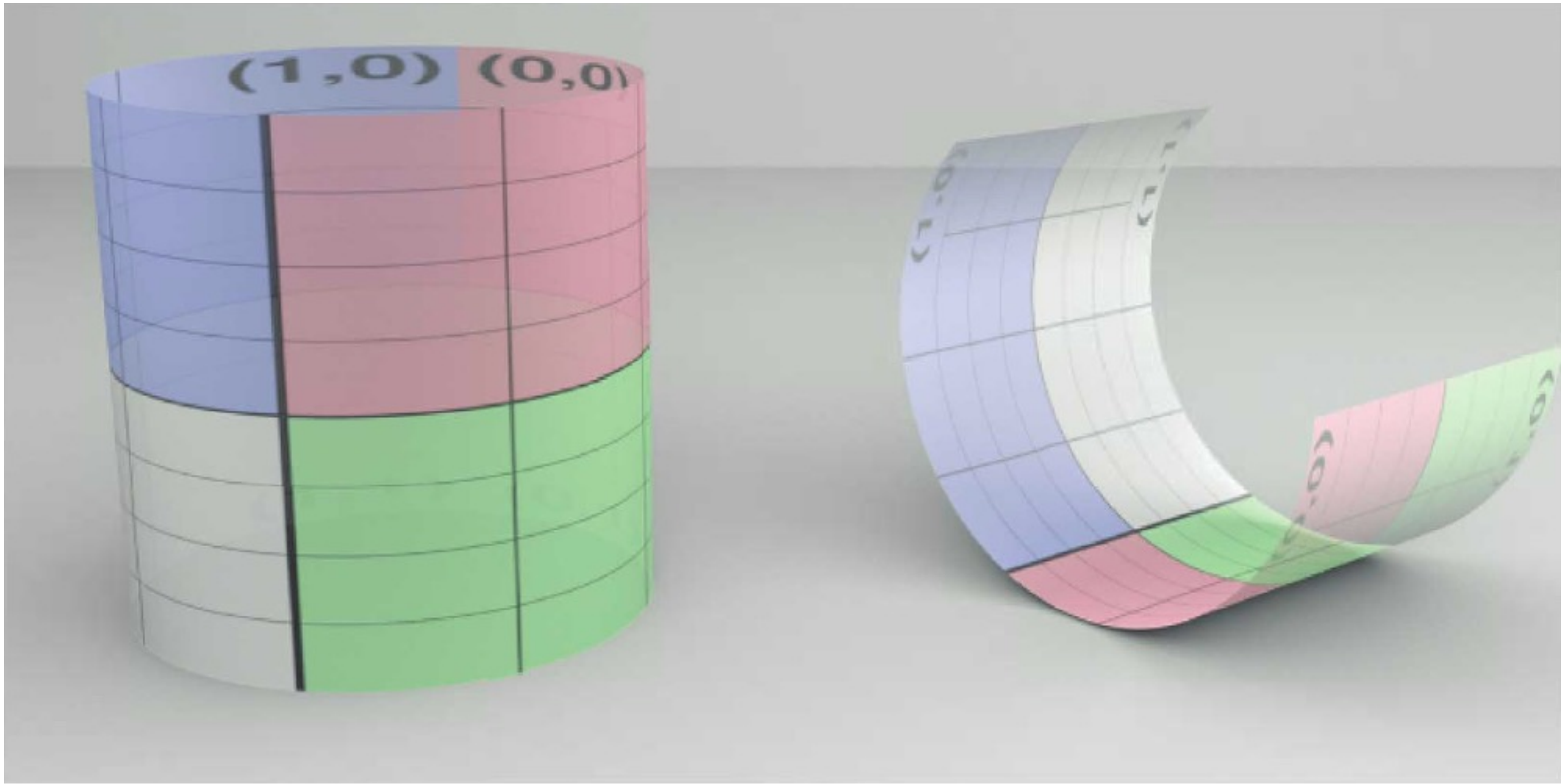
- **Polar Coordinates**
  - (x, y, 0) = Polar2Cartesian(r, φ)
- **Disc**
  - p(u, v) = Polar2Cartesian(R v, 2 π u) // disc radius R



Parametric Surfaces

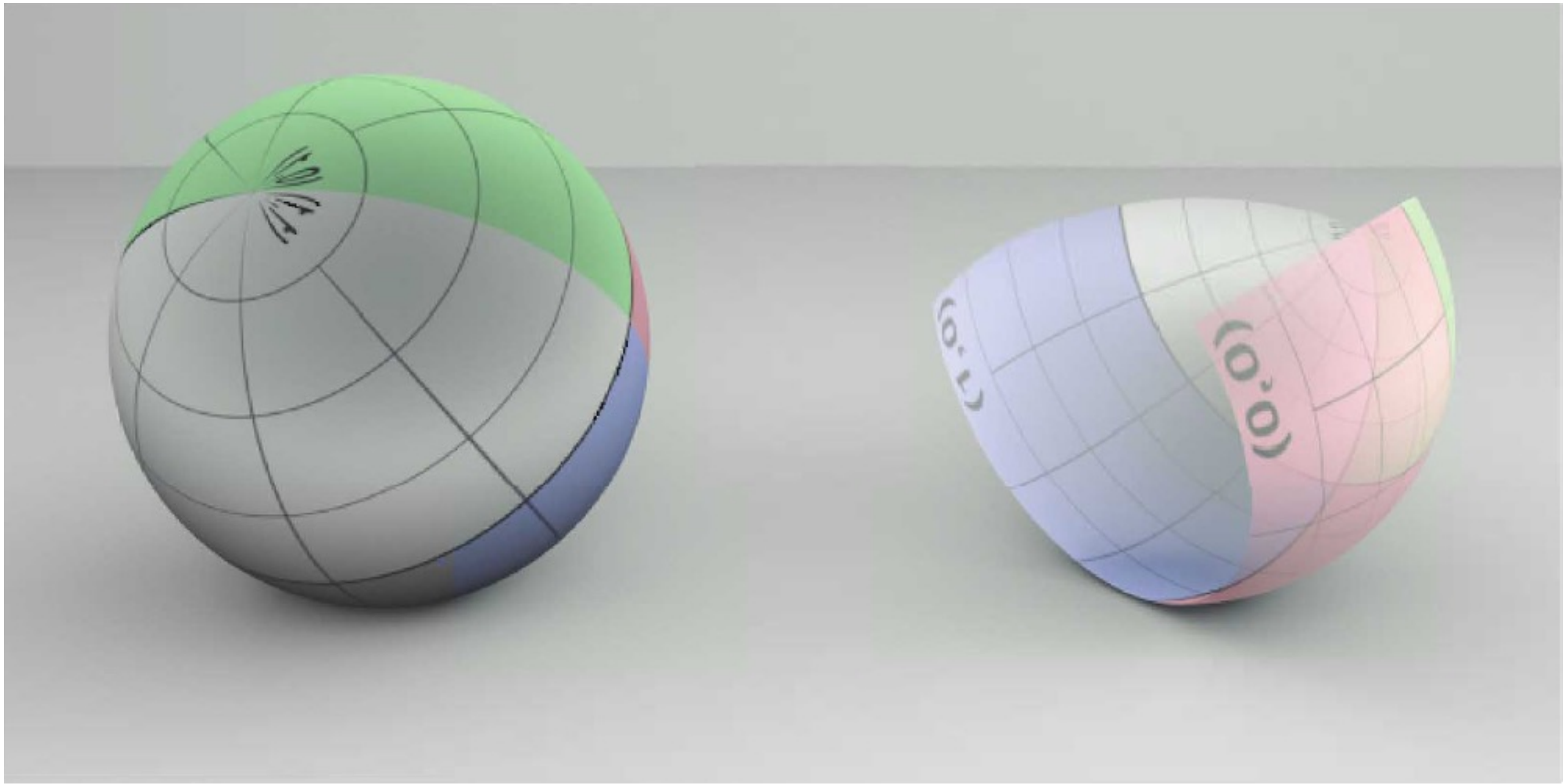


- **Cylindrical Coordinates**
  - (x, y, z) = Cylindrical2Cartesian(r, φ, z)
- **Cylinder**
  - p(u, v) = Cylindrical2Cartesian(r, 2 π u, H v)   // cylinder height H



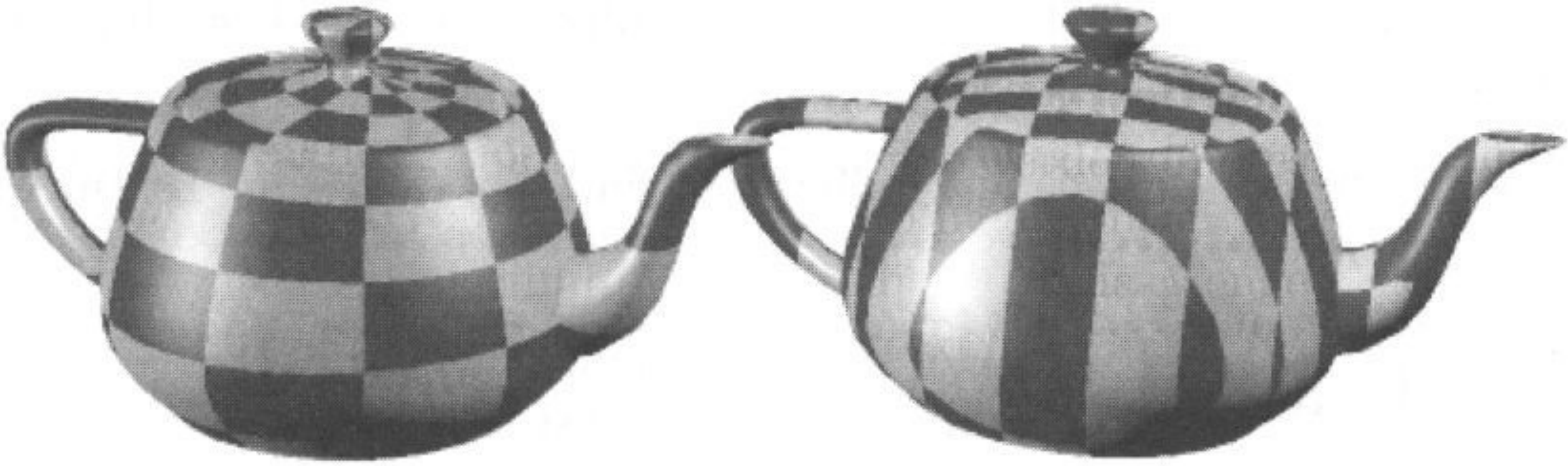
Parametric Surfaces

- **Spherical Coordinates**
  - (x, y, z) = Spherical2Cartesian(r, θ, φ)
- **Sphere**
  - p(u, v) = Spherical2Cartesian(r, π v, 2 π u)



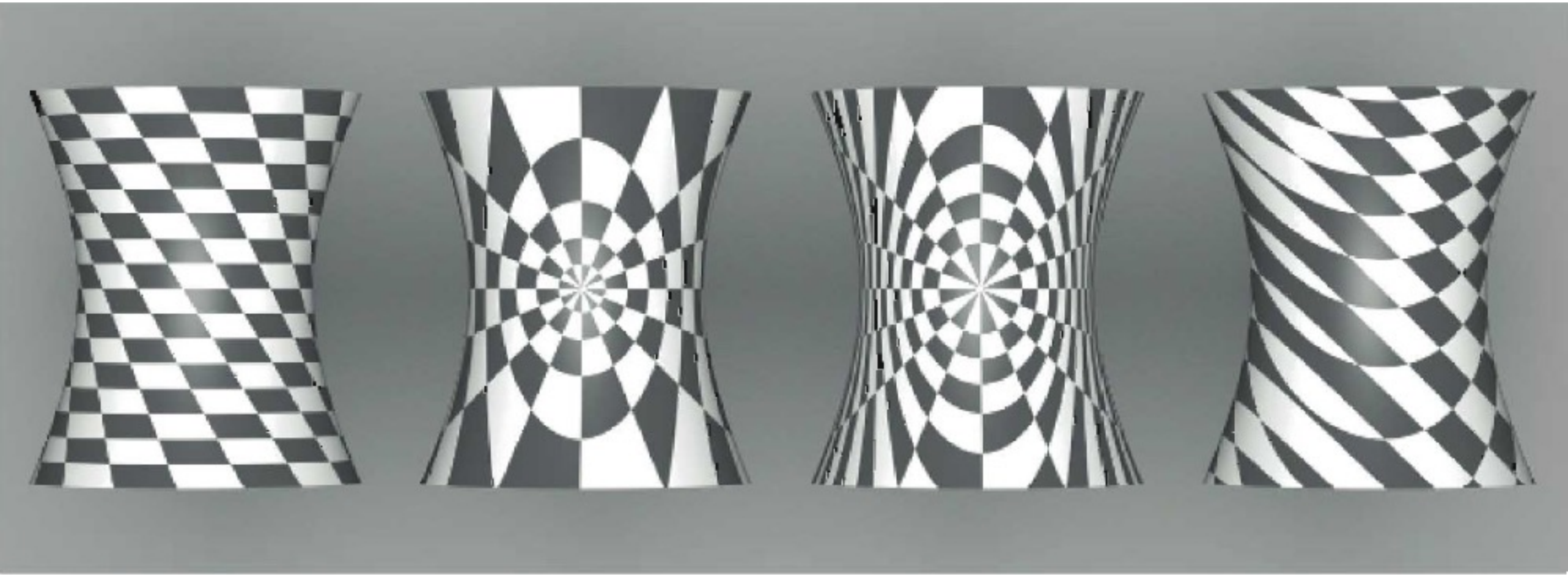
Surface Parameterization

- **Other Surfaces**
  - No intrinsic parameterization??



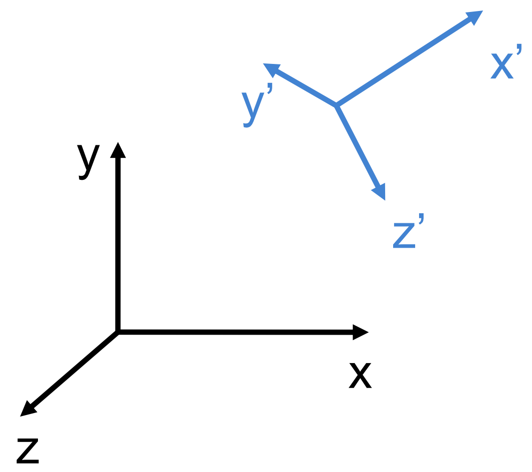
Intermediate Mapping

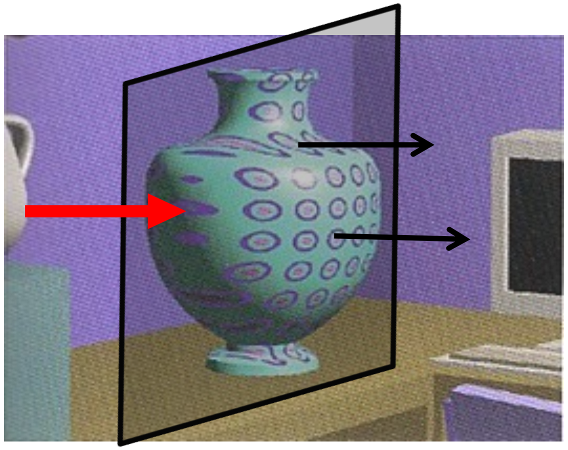
- **Coordinate System Transform**
  - Express Cartesian coordinates into a given coordinate system
- **3D to 2D Projection**
  - Drop one coordinate
  - Compute u and v from remaining 2 coordinates



Intermediate Mapping

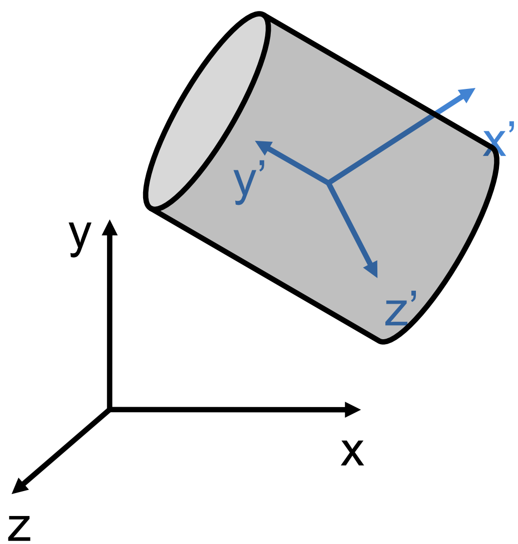
- **Planar Mapping**
  - Map to different Cartesian coordinate system
  - (x’, y’, z’) = AffineTransformation(x, y, z)
    - Orthogonal basis: translation + row-vector rotation matrix
    - Non-orthogonal basis: translation + inverse column-vector matrix
  - Drop z’, map u = x’, map v = y’
  - E.g.: Issues when surface normal orthogonal to projection axis

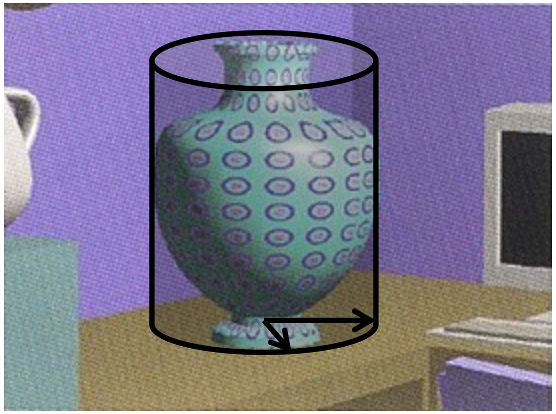




Intermediate Mapping

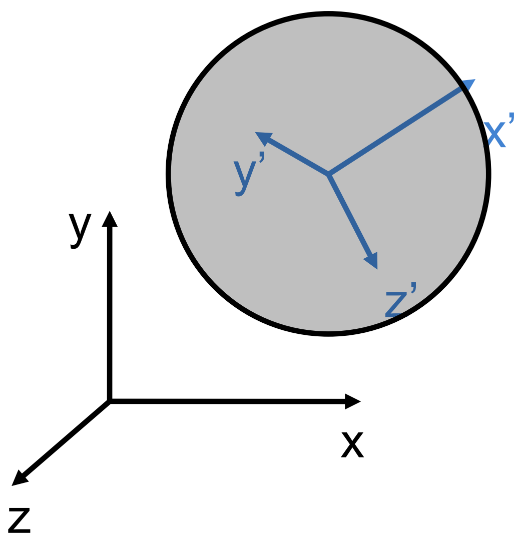
- **Cylindrical Mapping**
  - Map to cylindrical coordinates (possibly after translation/rotation)
  - $(r, \varphi, z) = \text{Cartesian2Cylindrical}(x, y, z)$
  - Drop r, map $u = \varphi / 2\pi$, map $v = z / H$
  - Extension: add scaling factors: $u = \alpha \varphi / 2\pi$
  - E.g.: Similar topology gives reasonable mapping

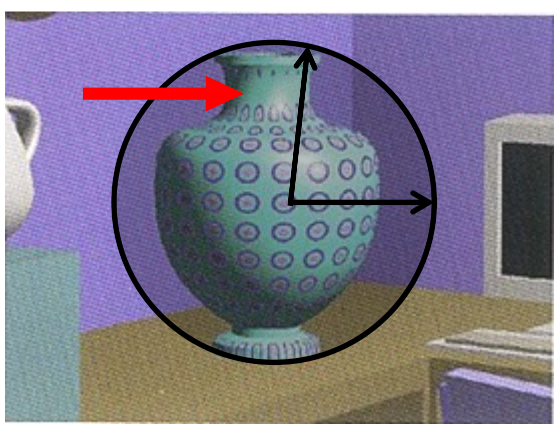




Intermediate Mapping

- **Spherical Mapping**
  - Map to spherical coordinates (possibly after translation/rotation)
  - $(r, \theta, \varphi) = \text{Cartesian2Spherical}(x, y, z)$
  - Drop r, map $u = \varphi / 2\pi$, map $v = \theta / \pi$
  - Extension: add scaling factors to both u and v
  - E.g.: Issues in concave regions



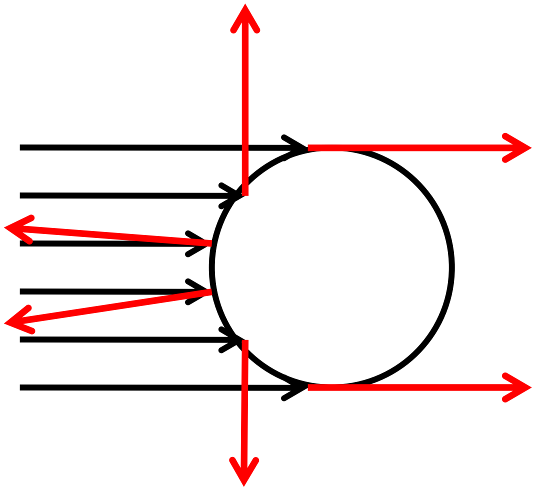


Slope-Based Mapping

- **Definition**
  - Depends on surface normal and predefined vector
- **Example**
  - $\alpha = n \boxed{?} \omega$
  - return α flatColor + (1 - α) slopeColor;

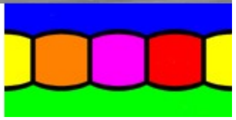
Environment Map

- **Spherical Map**
  - Photo of a reflective sphere (gazing ball)
  - Photos with a fish-eye camera



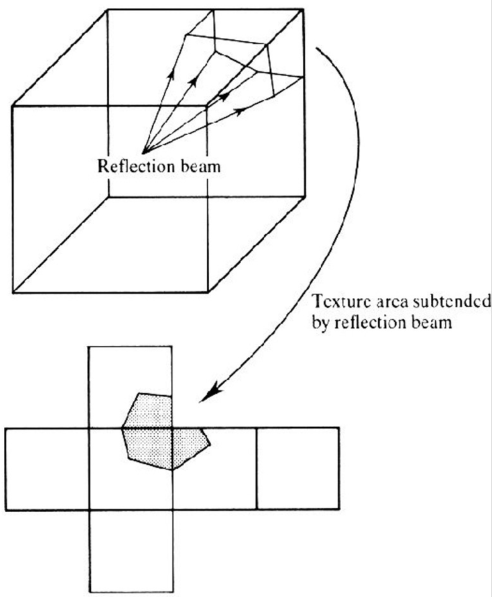
Environment Map

- **Latitude-Longitude Map**
  - Remapping 2 images of reflective sphere
  - Photo with an environment camera
- **Algorithm**
  - Hit infinitely far (parallax-free) background if no intersection found
  - Cartesian coords of ray dir. → spherical coords → uv tex coords



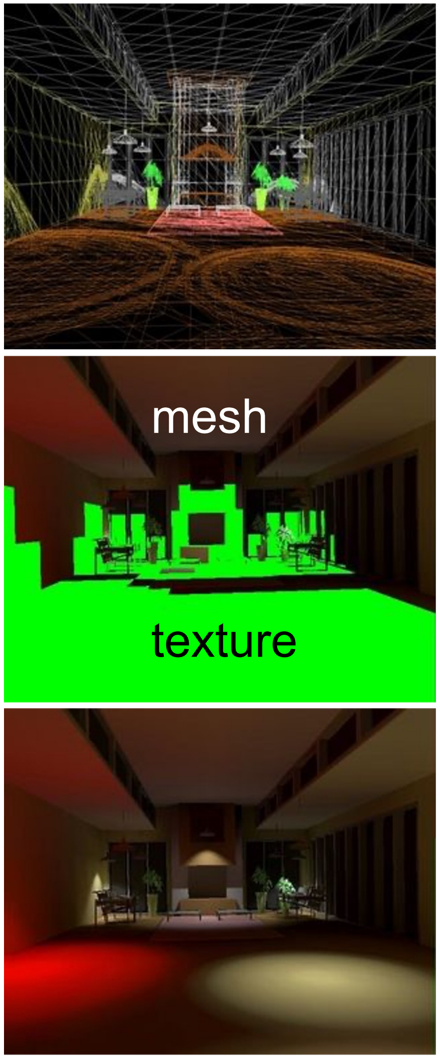
Environment Map

- **Cube Map**
  - Remapping 2 images of reflective sphere
  - Photos with a perspective camera
- **Algorithm**
  - Find main axis (-x, +x, -y, +y, -z, +z) of ray direction
  - Use other 2 coordinates to access corresponding face texture
    - Akin to a 90° projective light



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…



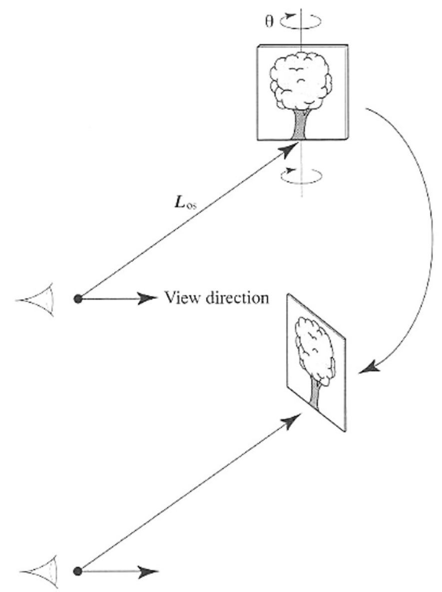
Representing radiosity in a mesh or texture

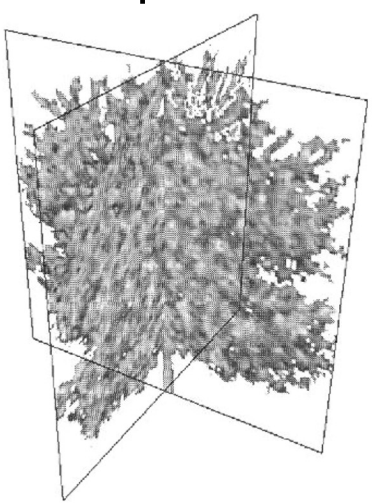
Reflectance Irradiance Radiosity

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

Billboards / Transparency Map

- **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 orientations
  - Complex distribution: trunk, branches, …





Opacity texture