Synthesis and Rendering of 3D Textures

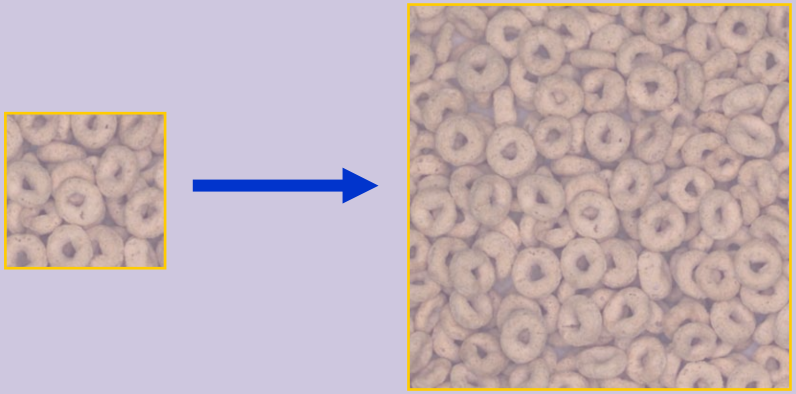
Yacov Hel-Or IDC, Israel (HP Labs)

Tom Malzbender HP Labs

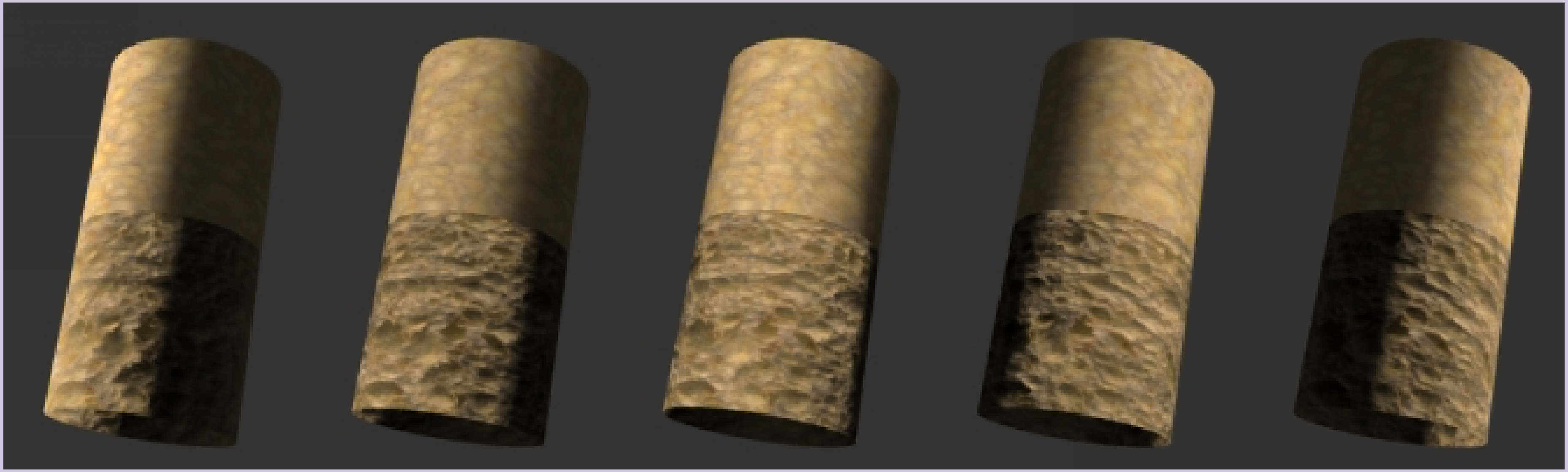
Dan Gelb HP Labs

Motivation

- Example Based Texture Synthesis is the process of generating novel texture images that are perceived similar to a given texture example.



- In typical texture synthesis approaches lighting condition is fixed, thus the synthesized textures have the same lighting condition “baked in”.



- A significant improvement in terms of visualization would be to synthesize textures so that a rendered textured object can be visualized under various lighting conditions

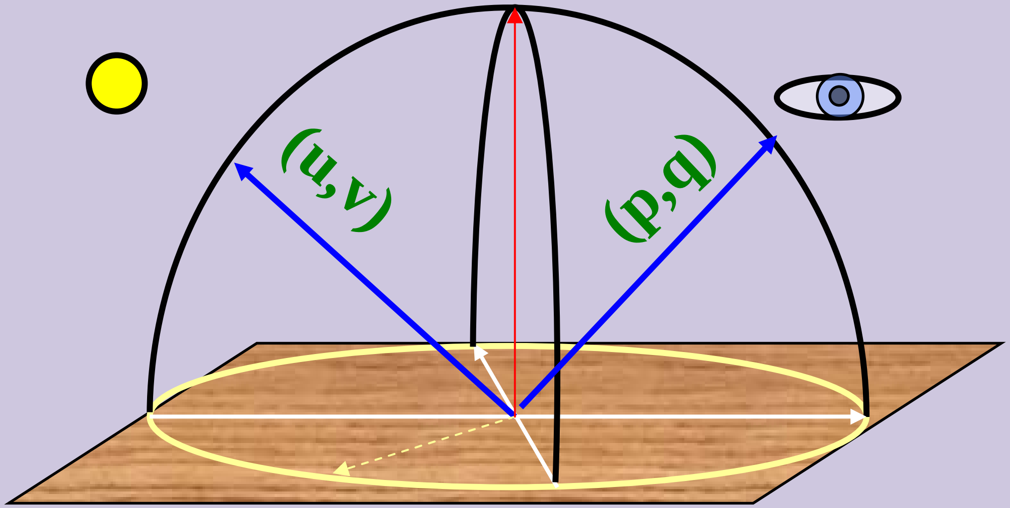
3D Texture Representation

- The appearance of a surface patch can be represented by the Bidirectional Texture Function (BTF):

$$\text{BTF:} \quad L_{[r,g,b]}(x,y,u,v,p,q)$$

- For a fixed viewing position we define a Unidirectional Texture Function (UTF):

$$\text{UTF:} \quad L_{[r,g,b]}(x,y,u,v)$$



Goal:

Given a UTF function, synthesize a novel UTF with similar statistical characteristics, such that it is perceived as a similar texture under all illumination directions. (Julez conjecture)

Notes:

- A “static” texture has specific statistical characteristics over pixel values. UTF has statistical characteristics over functions. Hence, the problem is computationally demanding.
- Using the UTF we sacrifice the ability to characterize view dependence phenomena, however, it is extremely easy to capture UTF functions of real world materials.

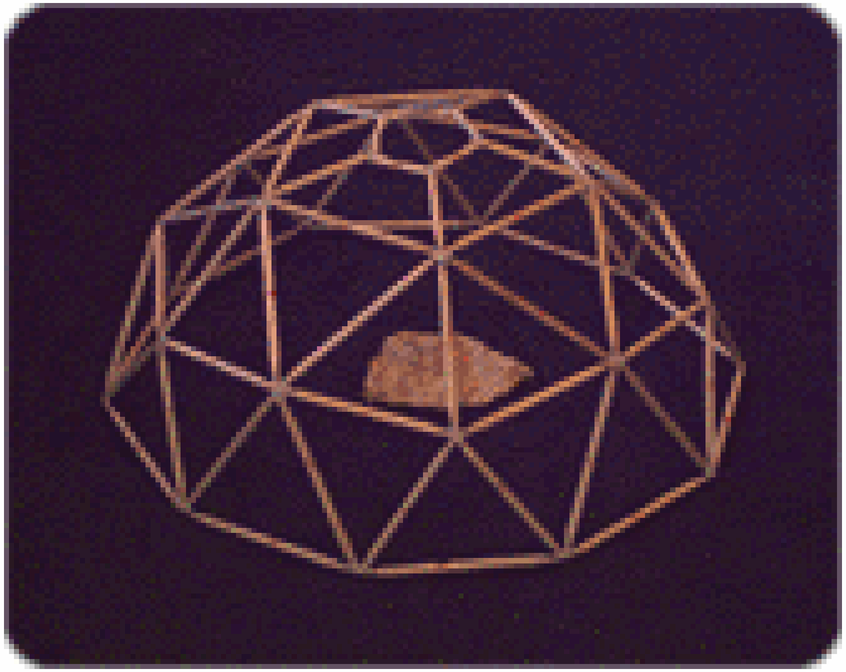


photo of the original dowel tempate

current electronically controlled flash based dome

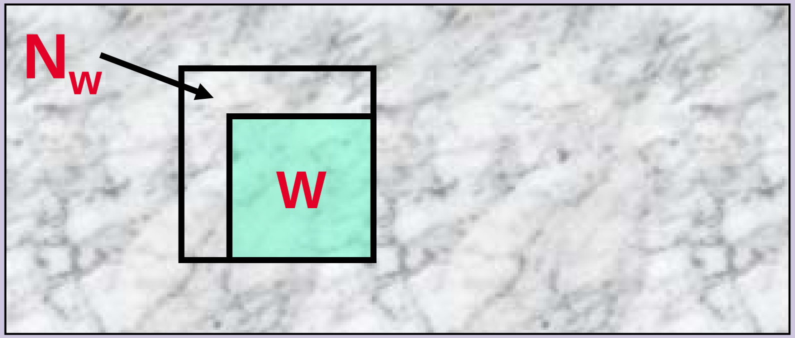
Window Based (Static) Texture Synthesis

Liang, Efros, Freeman

- Viewing a texture as a realization of an homogenous Markovian process, the p.d.f. of a texture window is characterized by its causal spatial neighborhood:

$$P(W \mid N_W) = P(W \mid I)$$

- Sampling from $P(W|N_W)$ is emulated by choosing a random window amongst all windows Q satisfying:



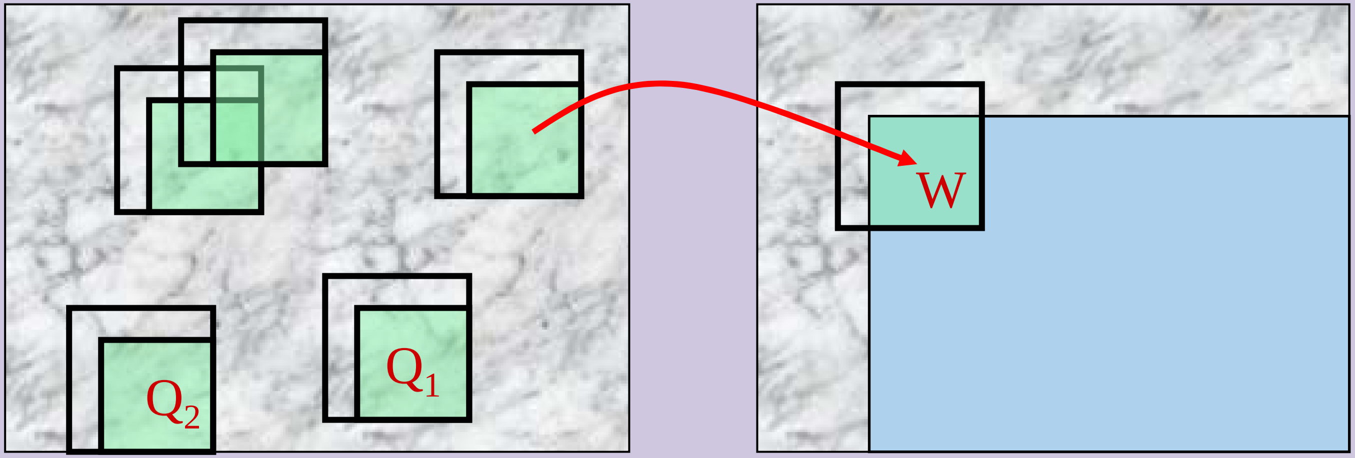
$$\| N_Q - N_W \| < \delta$$

Synthesis Algorithm:

- A novel texture patch is synthesized sequentially, window after window, mimicking the Markovian process.

- Given a window W to be synthesized with a known neighborhood, N_W , a window is selected randomly from amongst all windows {Q}, in the texture example, satisfying:

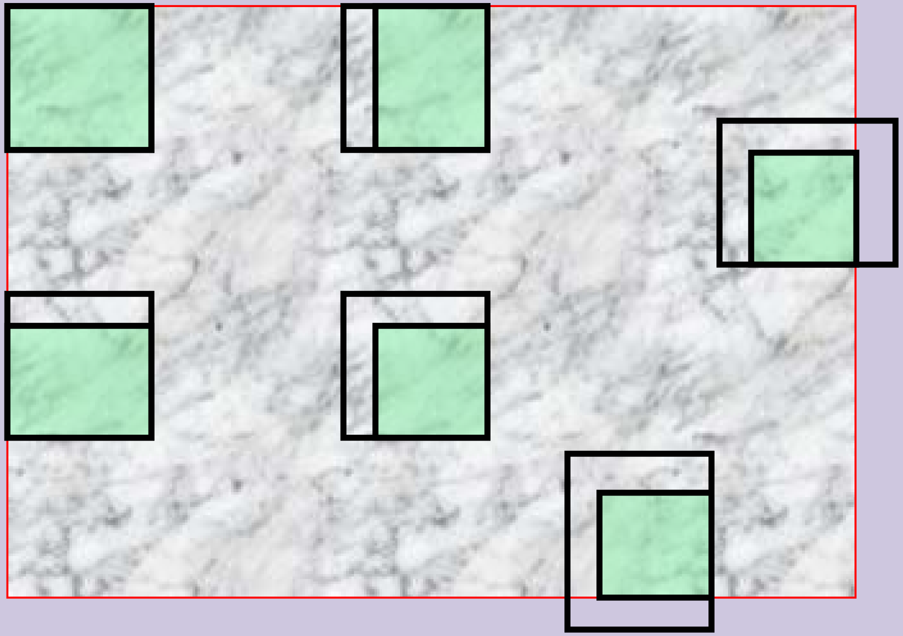
$$|| N_Q - N_W || < \delta$$



- The acquired windows are concatenated together using alpha-blending, or optimal boundary cuts are calculated.

- Border windows are treated differently.

- Tileable synthesis is easily treated.



UTF Texture Synthesis

- We view a UTF as a texture of functions - $L(u,v)$ (rather than textures of pixels).
- Along with this view, a function index $\psi\{L(u,v)\} \in \Psi$ is assigned to each pixel's reflectance function.
- The function index ψ is regarded as a random variable over which the stochastic process is defined.
- A UTF patch can be viewed as a realization of a Markovian stochastic process over function indices:

$$P(\psi\{W\} \mid \psi\{N_W\})$$

Assume samples of a specific UTF are given from which a novel UTF is to be synthesized.

- Two main problems:
  - How is a continuous UTF reconstructed from its samples?
  - What is the UTF function index over which the p.d.f. is defined?

Both problems are resolved using the *PTM* representation.

PTM Images

- The Polynomial Texture Format (PTM) is an image format, (suggested by Malzbender et.al. 2001), compactly encoding an image appearance under various lighting directions.

- A set of images $\{L_k(x,y)\}$ are acquired under different lighting directions $\{(u_k,v_k)\}$.

- Polynomial fitting is applied to the acquired images:

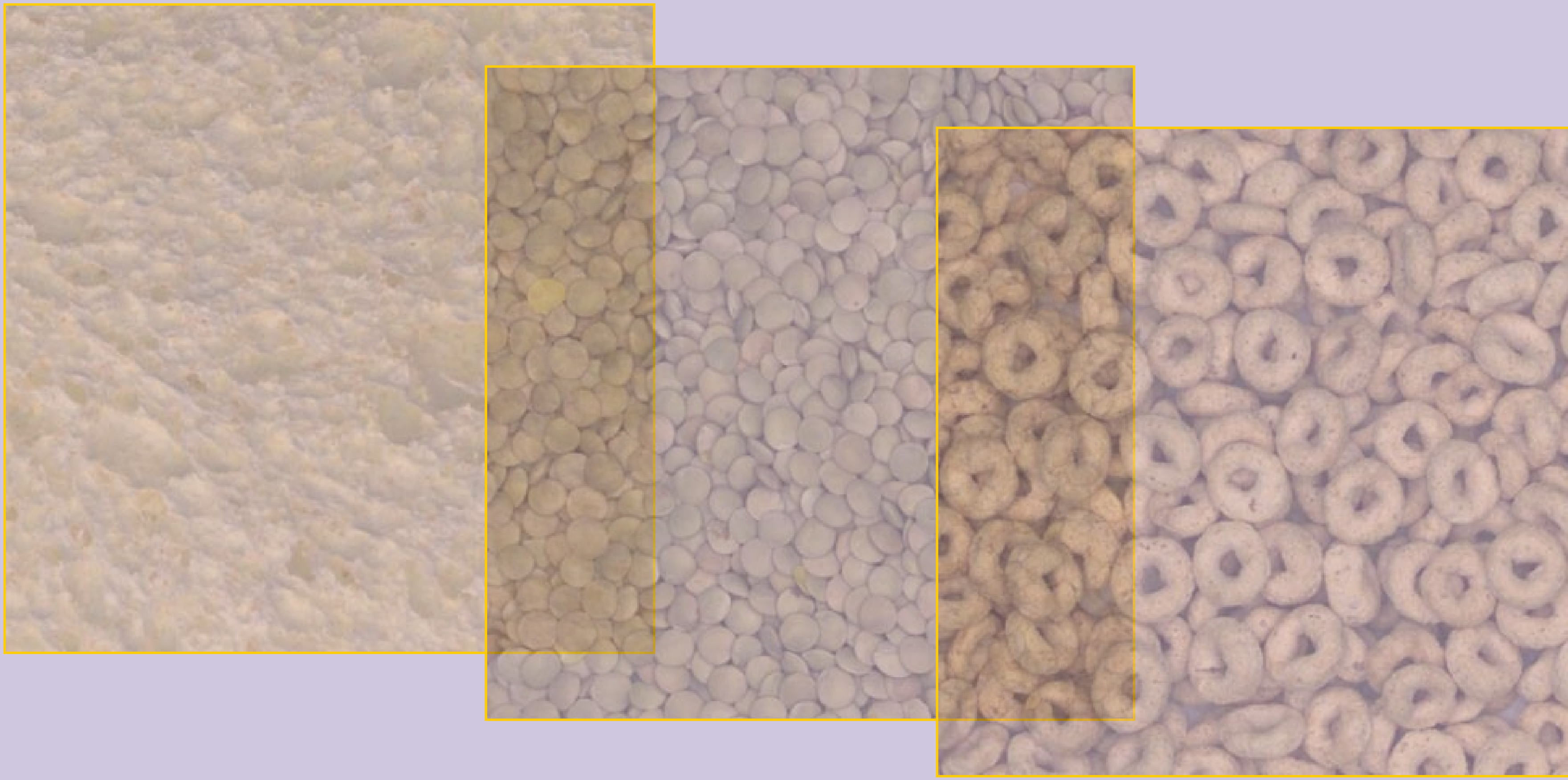
$$L(x,y,u,v)=\sum_{i,j} a_{i,j}(x,y)\,u^i v^j$$

$$s.t.\ \ Min\sum_k \left\| L(x,y,u_k,v_k)-L_k(x,y)\right\|_2$$

• • •

$$L(x,y;u,v) = \begin{bmatrix} 1 & u & v & uv & u^2 & v^2 \end{bmatrix} \begin{pmatrix} a_1(x,y) \\ a_2(x,y) \\ a_3(x,y) \\ a_4(x,y) \\ a_5(x,y) \\ a_6(x,y) \end{pmatrix}$$

More Examples



UTF Texture Synthesis

- A PTM pixel's coefficients can be treated as a function index:

$$\psi\{L(x,y,u,v)\} = \overline{a}(x,y)$$

where

$$\overline{a}(x,y) = \{a_1(x,y) \cdots a_6(x,y)\}$$

- However, the transformation from function space into index space does NOT preserve function distance:

$$\int \left\| L_\alpha(u,v) - L_\beta(u,v) \right\|_2 du\, dv \neq \left\| \overline{a}_\alpha - \overline{a}_\beta \right\|_2$$

which implies that

$$P(W) \neq P(\psi\{W\})$$

- In order to work directly with function index, the UTF representation is transformed into an orthogonal basis (2D Legendre polynomial basis):

$$B = \left\{ \frac{1}{2}, \frac{\sqrt{3}}{2}u, \frac{\sqrt{3}}{2}v, \frac{3}{2}uv, \frac{\sqrt{45}}{4}u^2 - \frac{\sqrt{45}}{12}, \frac{\sqrt{45}}{4}v^2 - \frac{\sqrt{45}}{12} \right\}$$

using a linear transformation:

$$\bar{a}(x,y) \Rightarrow \bar{b}(x,y) \quad where\ \bar{b} = M\bar{a}$$

- Using $b(x,y)=\psi\{L(x,y,u,v)\}$ as the function index implies:

$$P(W) = P(\psi\{W\})$$

UTF Synthesis Algorithm:

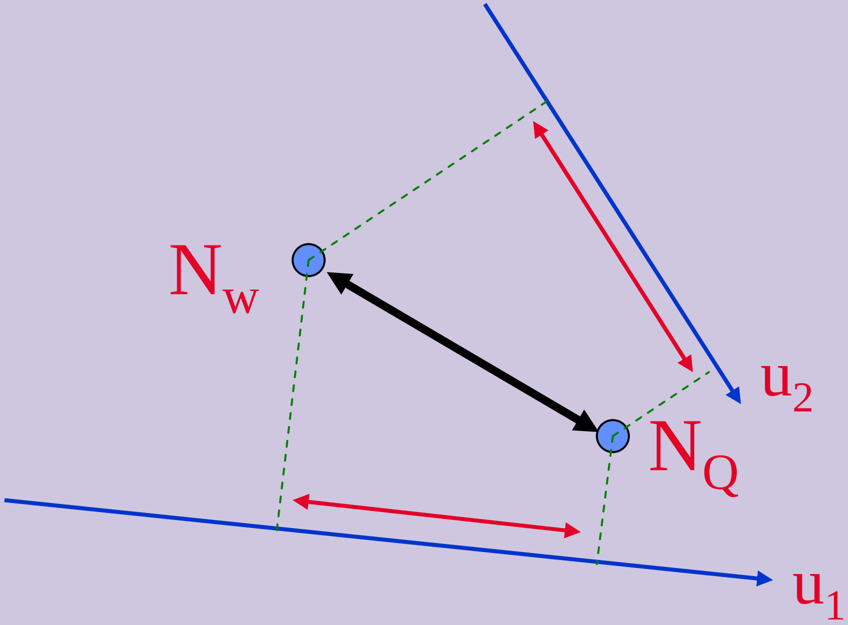
- A novel UTF patch is synthesized sequentially, window after window, mimicking the Markovian process.
- Given a window $W(x,y)$ to be synthesized with a known neighborhood, $N_W(x,y)$, a window is selected randomly from amongst all windows $\{Q\}$, in the texture example, satisfying:

$$\sum_{x,y} \left\| \psi\left\{N_Q(x,y)\right\} - \psi\left\{N_W(x,y)\right\} \right\|_2 \leq \delta$$

- The selected windows are concatenated using alpha-blending (or an optimal cut is performed) *in **b**-space*.

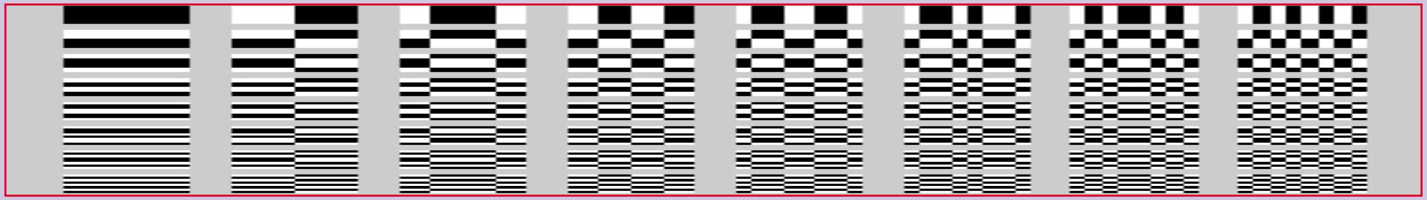
Search Strategy

- Fast search for “similar” window neighborhoods is applied using a projection kernel scheme [Hel-Or&Hel-Or, ICCV 03].
- Search time is expedites by 2 orders of magnitudes.



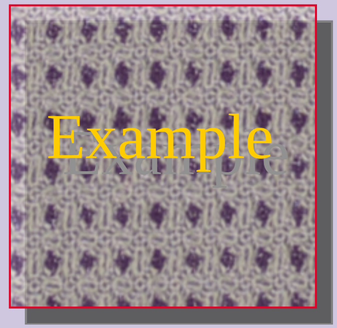
$$\left\| N_W - N_Q \right\|_2 \geq \sum_k f\left(u_k^T N_W , u_k^T N_Q \right)$$

- We use the Walsh-Hadamard projection kernels.
- WH kernels can be applied very fast in a recursive manner.
- After each projection, a large percentage of windows are rejected as their lower-bounds are above the pre-defined threshold δ.



Results

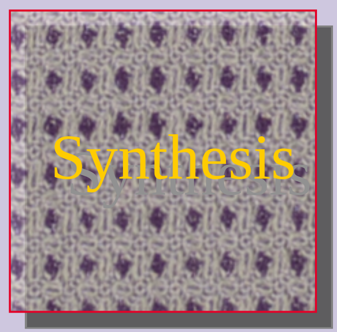
smallSeeds



smallfabric1c

smallcement

SynSeeds



fabric1c

cementtile

More Results

Tileable UTF

seedsWAsmall

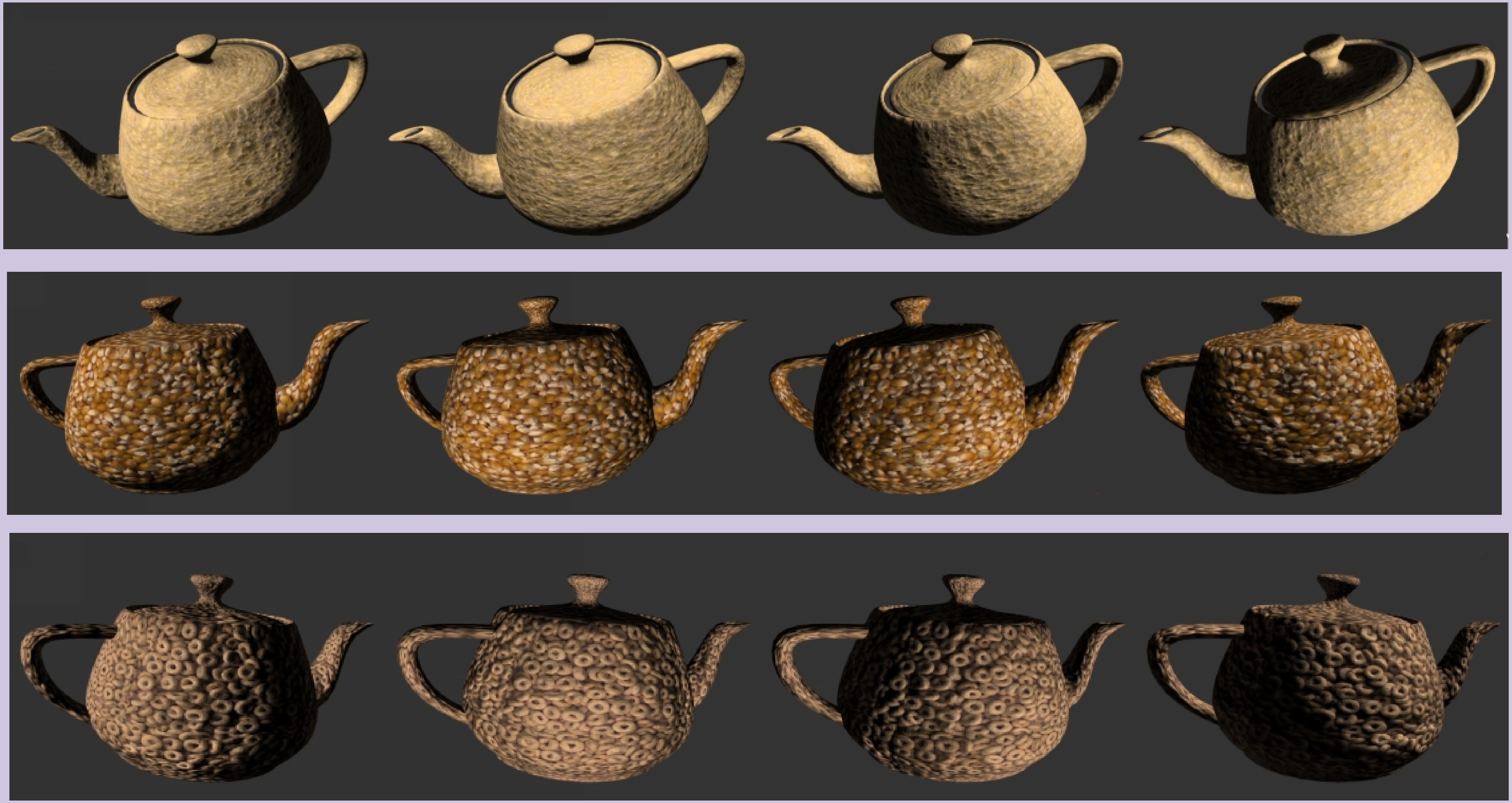
seedsWAx4

Multi-scale texture elements

sand

sandSyn

Synthesized PTM Mapping



Conclusion

- A 3D texture can be viewed as a realization of a Markovian stochastic process over function indices.
- The function index is represented by the function's coefficient using an orthogonal basis set of functions.
- The window based texture synthesis is applied directly on the function indices.
- Fast search of window neighborhoods is performed using the projection kernels scheme.