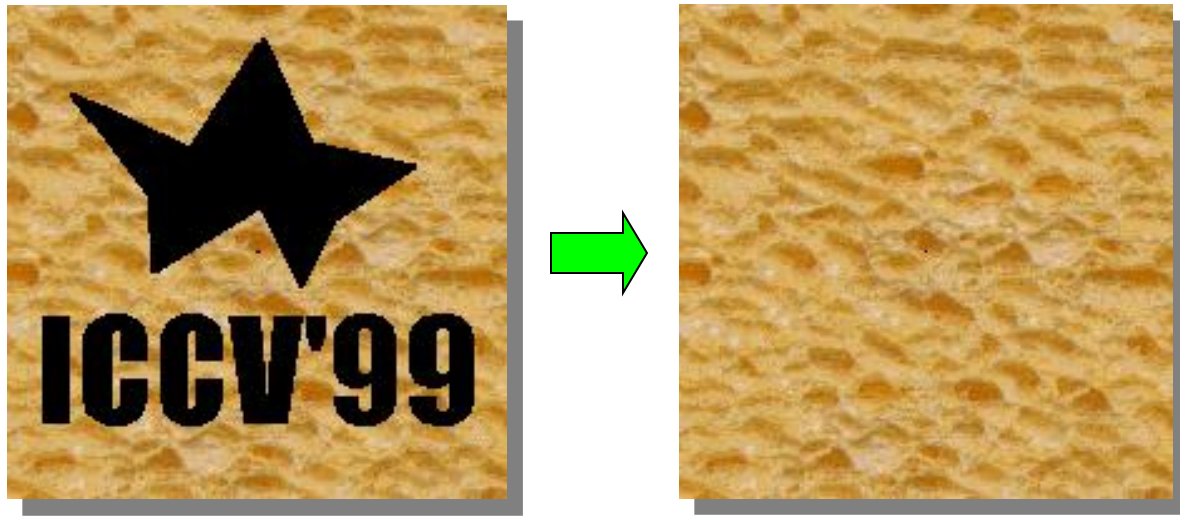
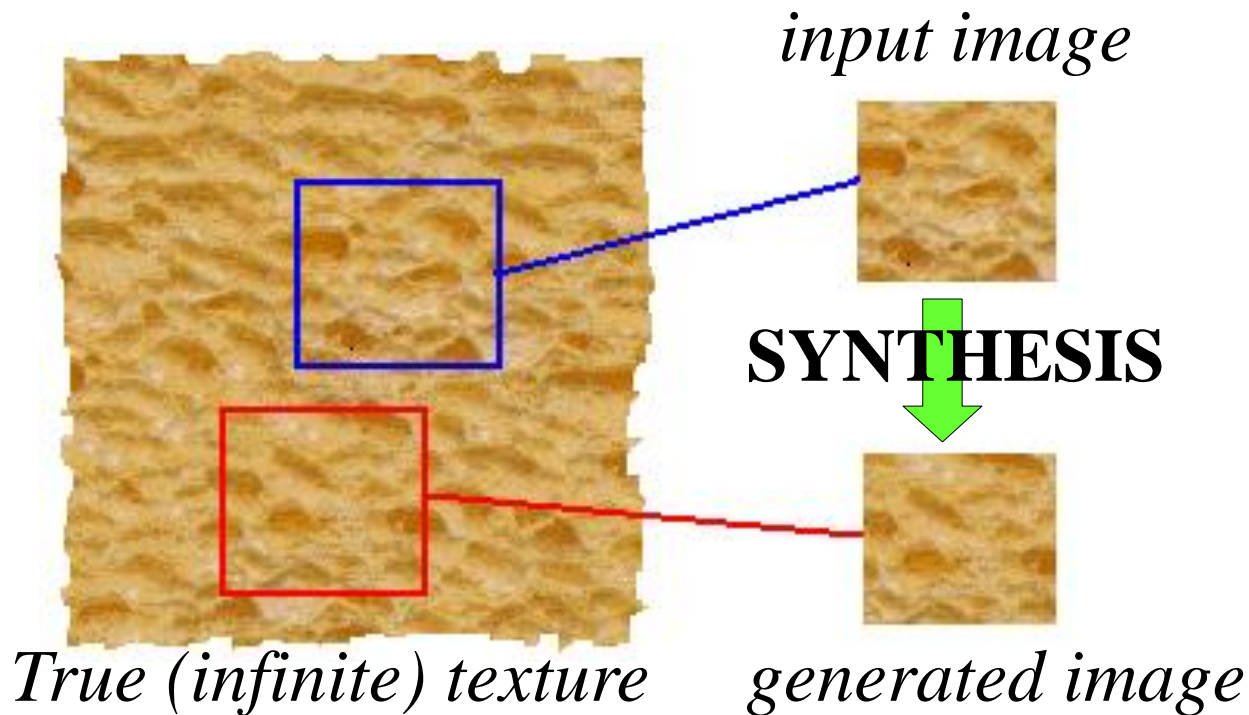


# Texture Synthesis by Non-parametric Sampling



*Alexei Efros and Thomas Leung*  
*UC Berkeley*

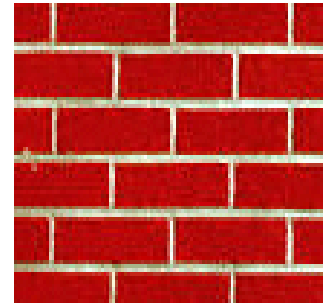
# Goal of Texture Synthesis



- Given a finite sample of some texture, the goal is to synthesize other samples from that same texture.
  - The sample needs to be "large enough"

# The Challenge

- Texture analysis: how to capture the essence of texture?
- Need to model the whole spectrum: from repeated to stochastic texture
- This problem is at intersection of vision, graphics, statistics, and image compression



**repeated**



**stochastic**



**Both?**

# Some Previous Work

- multi-scale filter response histogram matching [Heeger and Bergen, '95]
- sampling from conditional distribution over multiple scales [DeBonet, '97]
- filter histograms with Gibbs sampling [Zhu et al, '98]
- matching 1st and 2nd order properties of wavelet coefficients [Simoncelli and Portilla, '98]
- N-gram language model [Shannon, '48]
- clustering pixel neighbourhood densities [Popat and Picard, '93]

# Our Approach

- Our goals:
  - preserve local structure
  - model wide range of real textures
  - ability to do constrained synthesis
- Our method:
  - Texture is “grown” one pixel at a time
  - conditional pdf of pixel given its neighbors synthesized thus far is computed directly from the sample image

# Motivation from Language

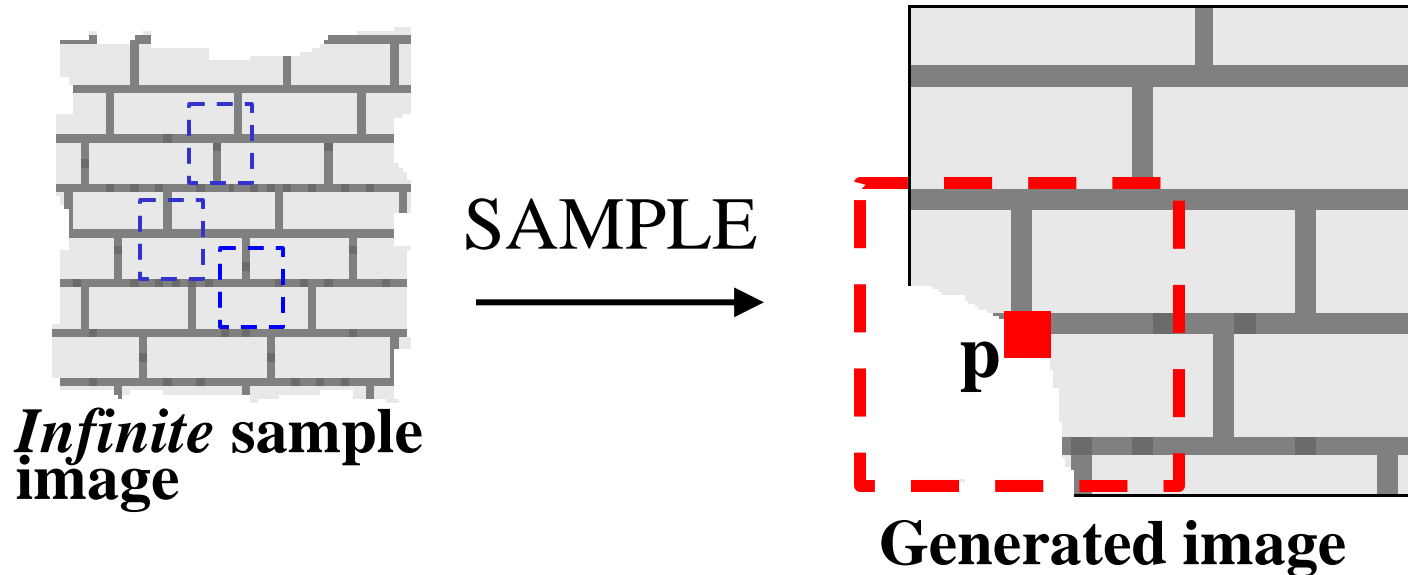
- [Shannon, '48] proposed a way to generate English-looking text using N-grams:
  - Assume a generalized Markov model
  - Use a large text to compute probability distributions of each letter given N-1 previous letters
    - precompute or sample randomly
  - Starting from a seed repeatedly sample this Markov chain to generate new letters
  - One can use whole words instead of letters too:

**WE NEED TO EAT CAKE**

# Mark V. Shaney (Bell Labs)

- Results (using alt.singles corpus):
  - *“As I've commented before, really relating to someone involves standing next to impossible.”*
  - *“One morning I shot an elephant in my arms and kissed him.”*
  - *“I spent an interesting evening recently with a grain of salt”*
- Notice how well local structure is preserved!
  - Now let's try this in 2D...

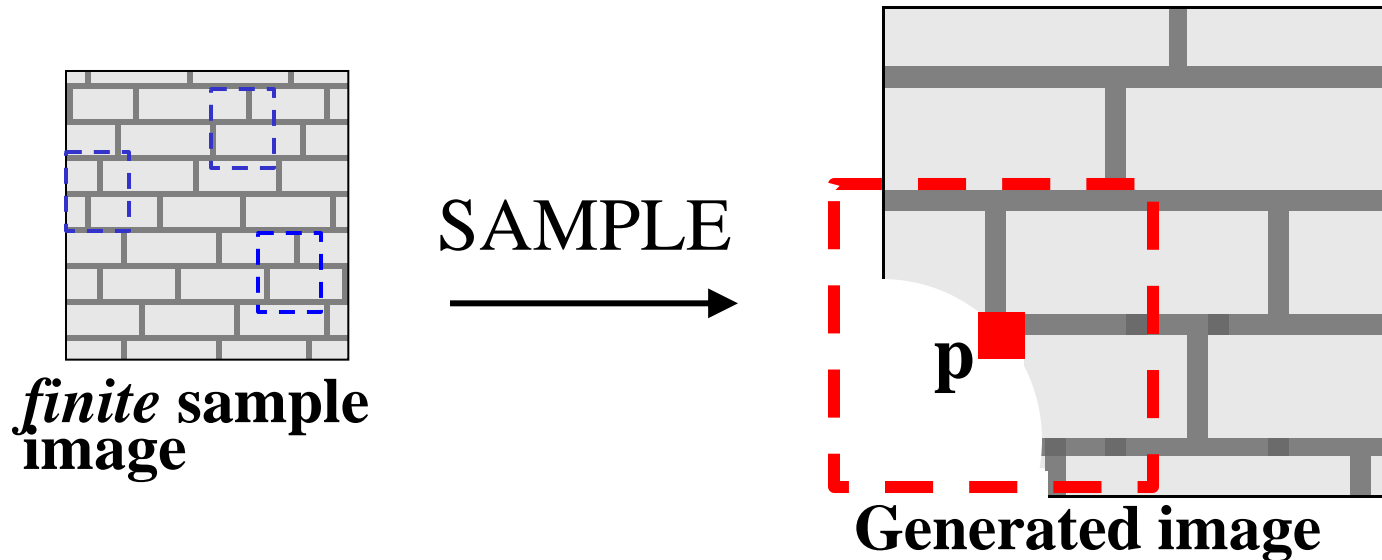
# Synthesizing One Pixel



- Assuming Markov property, what is conditional probability distribution of  $p$ , given the neighbourhood window?
- Instead of constructing a model, let's directly search the input image for all such neighbourhoods to produce a histogram for  $p$
- To synthesize  $p$ , just pick one match at random



# Really Synthesizing One Pixel



- However, since our sample image is finite, an exact neighbourhood match might not be present
- So we find the **best** match using SSD error (weighted by a Gaussian to emphasize local structure), and take all samples within some distance from that match

# Growing Texture

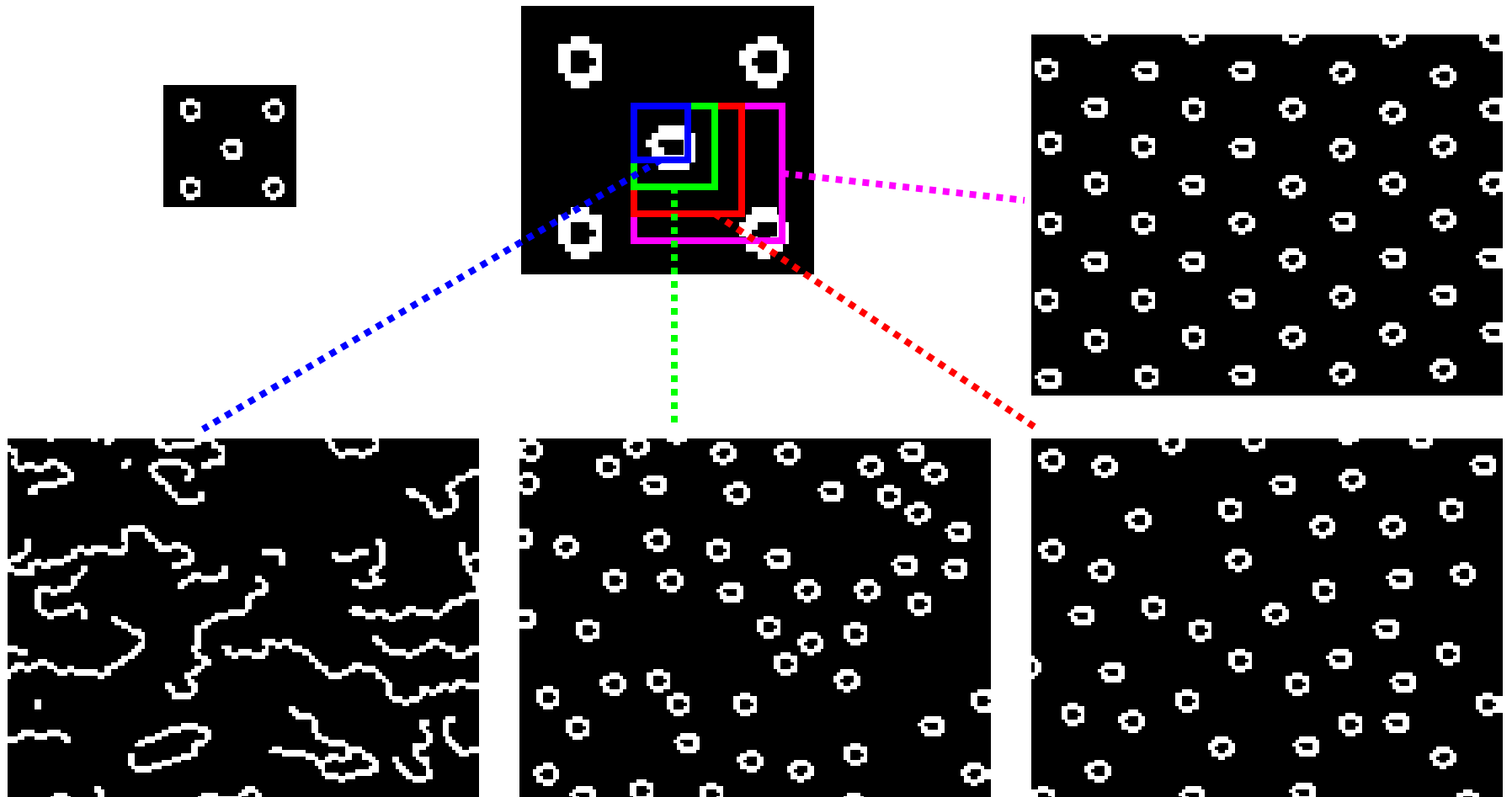


- Starting from the initial configuration, we “grow” the texture one pixel at a time
- The size of the neighbourhood window is a parameter that specifies how stochastic the user believes this texture to be
- To grow from scratch, we use a random 3x3 patch from input image as seed

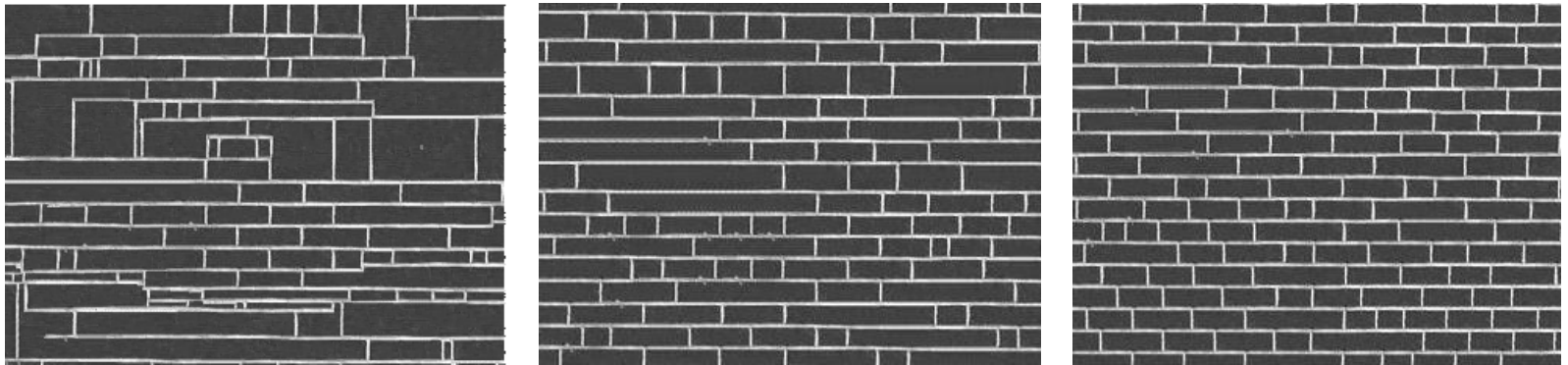
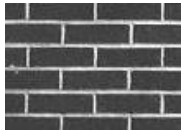
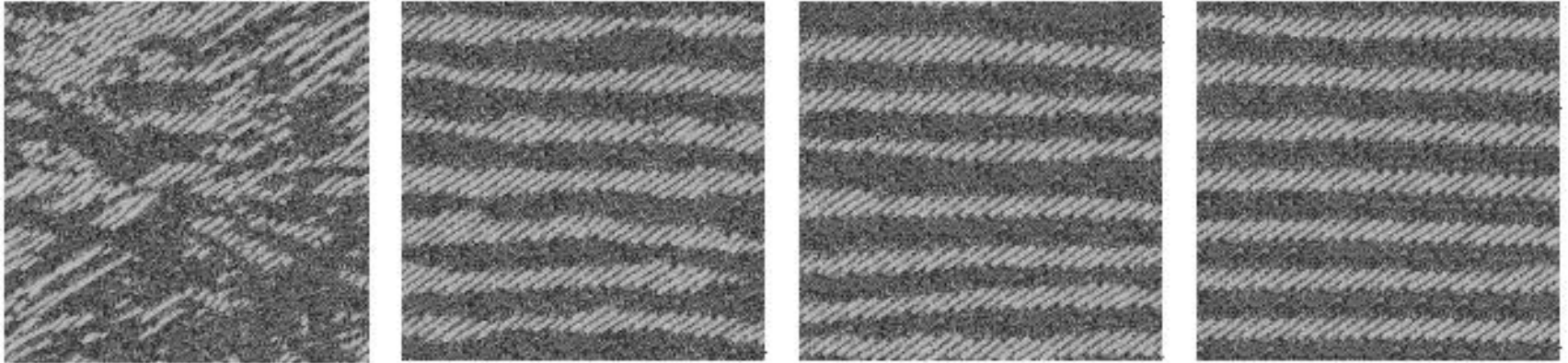
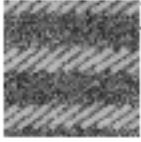
# Some Details

- Growing is in “onion skin” order
  - Within each “layer”, pixels with most neighbors are synthesized first
  - If no close match can be found, the pixel is not synthesized until the end
- Using *Gaussian-weighted* SSD is very important
  - to make sure the new pixel agrees with its closest neighbors
  - Approximates reduction to a smaller neighborhood window if data is too sparse

# Randomness Parameter



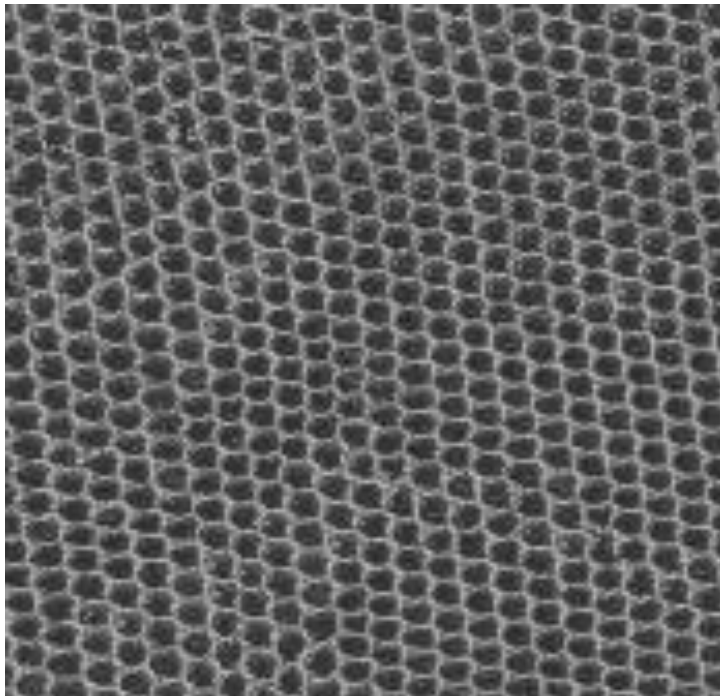
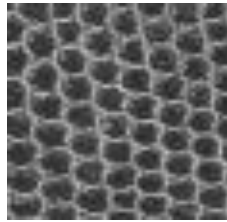
# More Synthesis Results



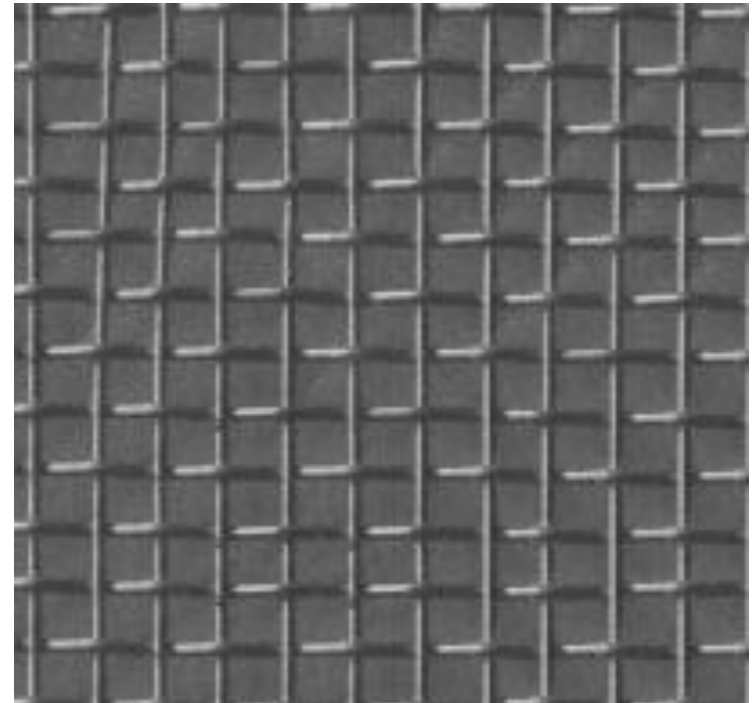
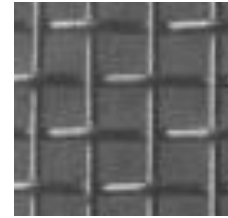
Increasing window size 

# Brodatz Results

reptile skin

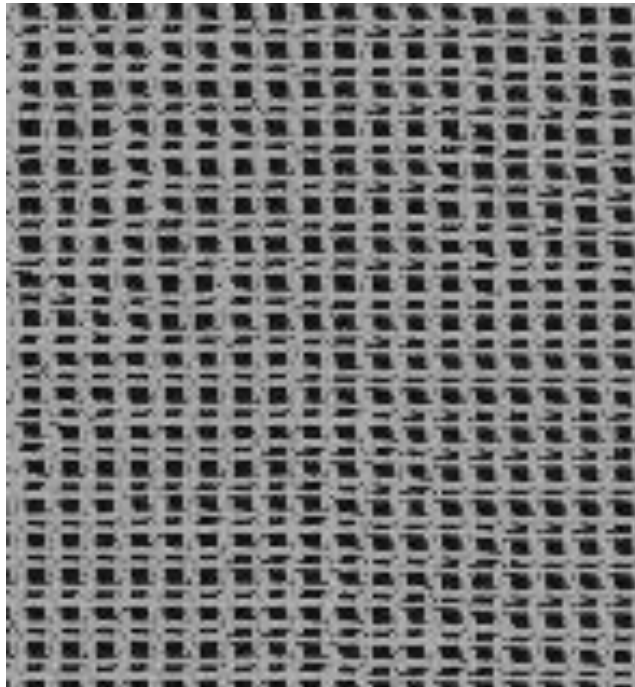
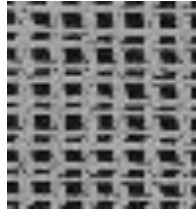


aluminum wire

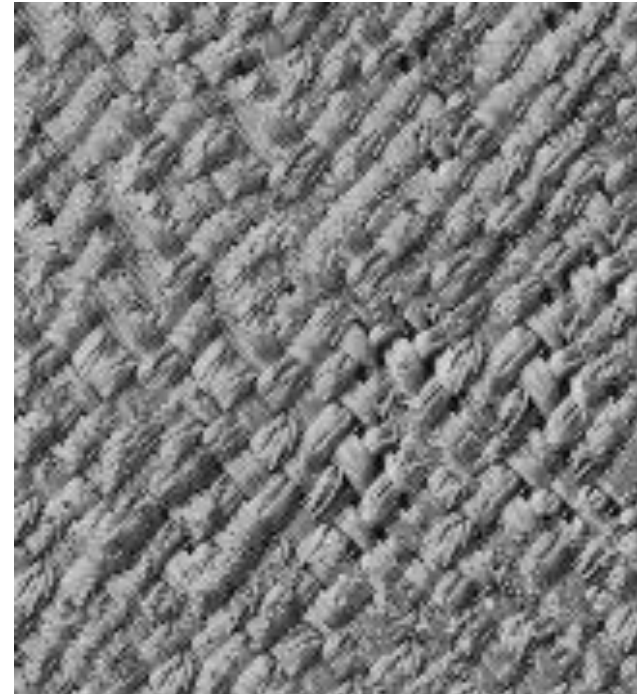


# More Brodatz Results

french canvas



rafia weave

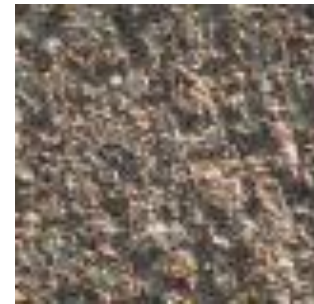


# More Results

wood



granite



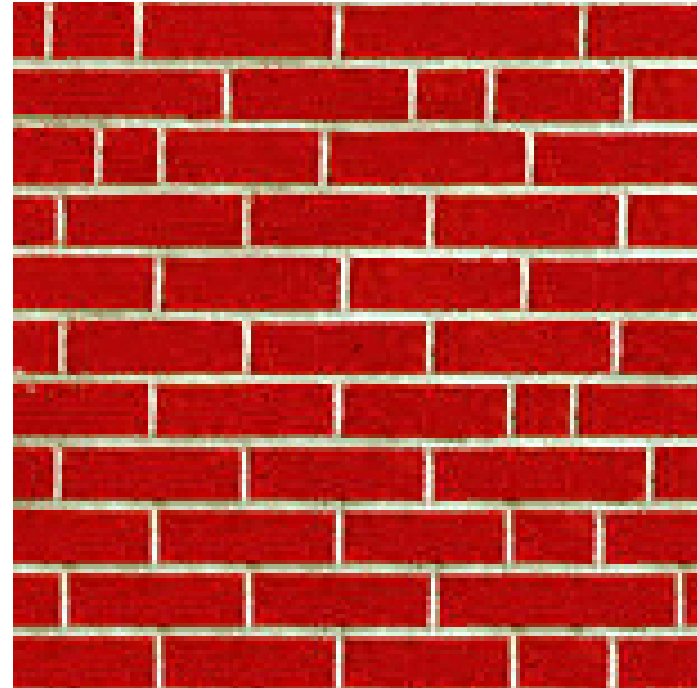
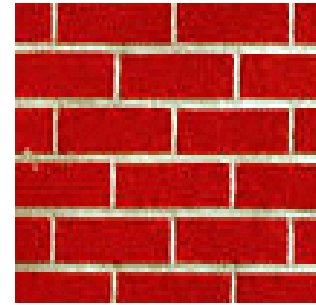


# More Results

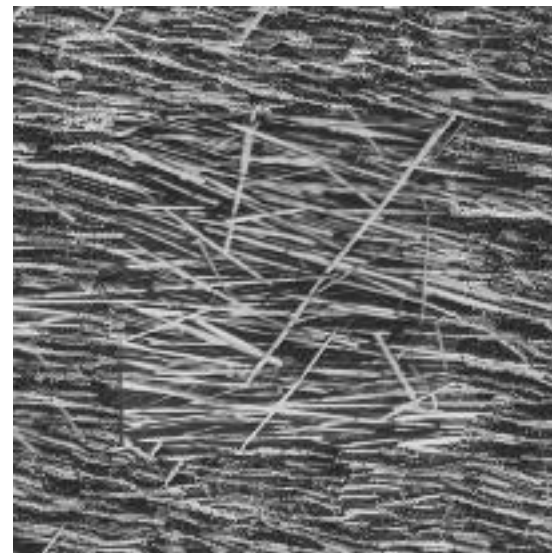
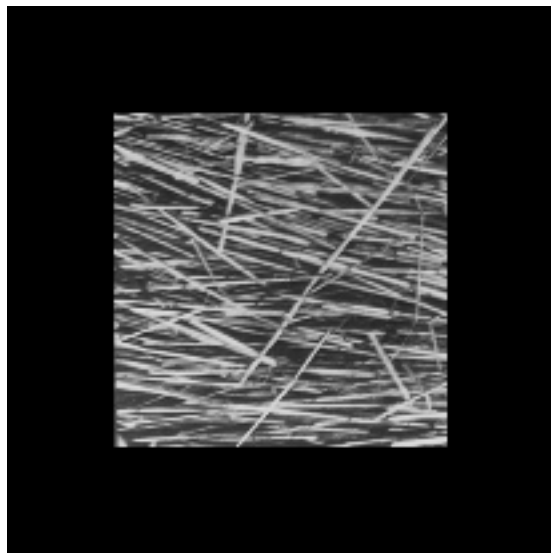
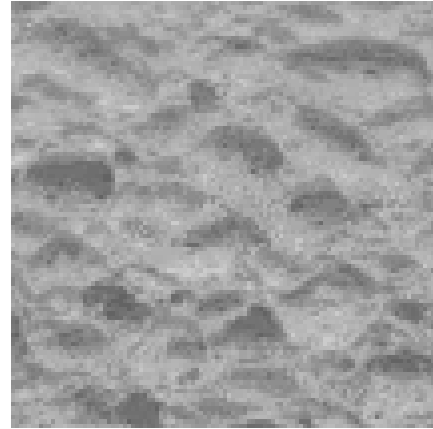
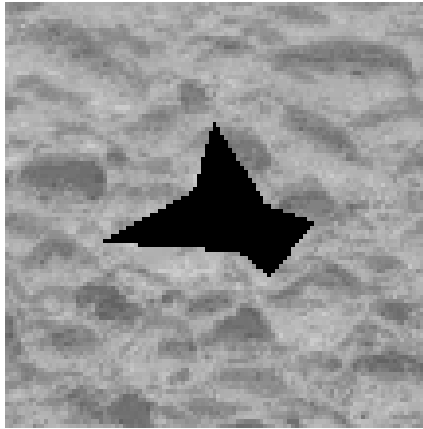
white bread



brick wall

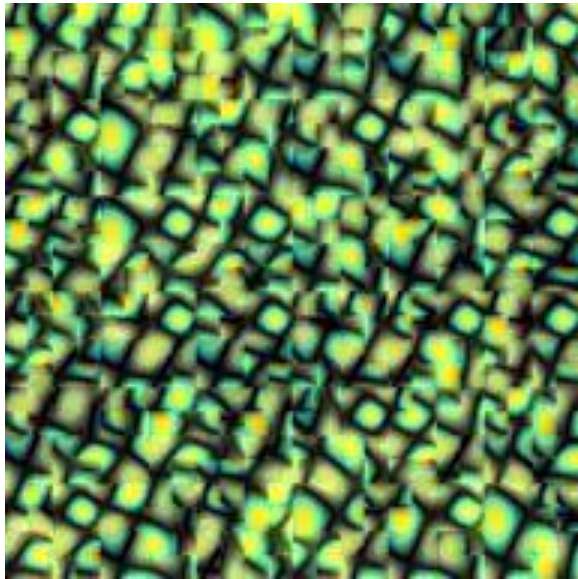
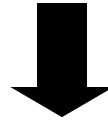
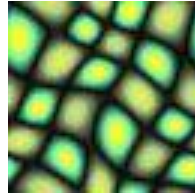


# Constrained Synthesis

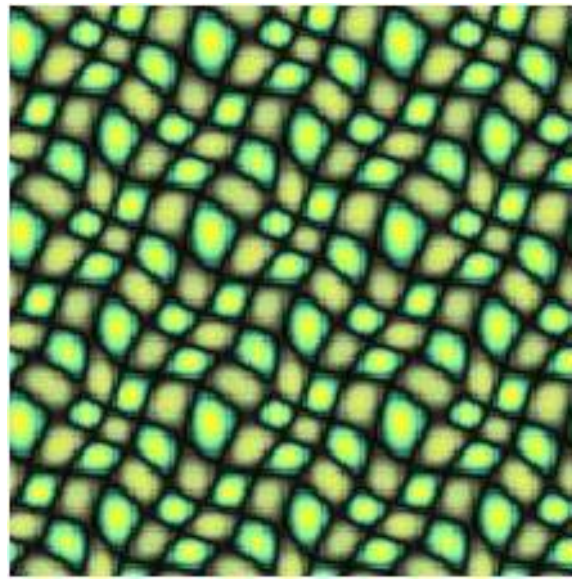


# Visual Comparison

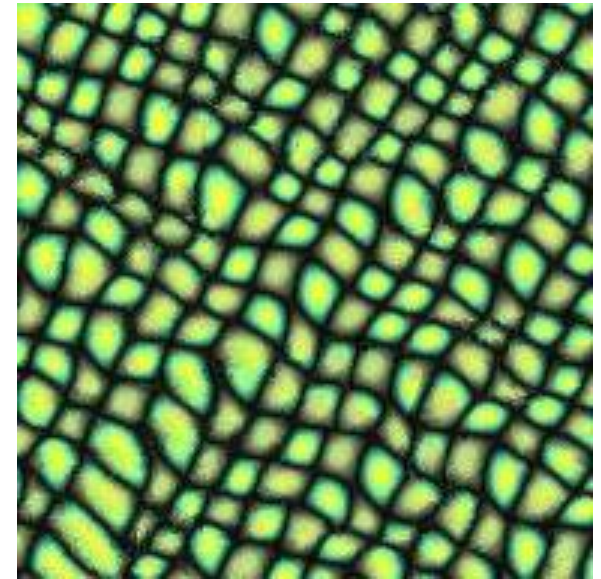
*Synthetic tilable  
texture*



**[DeBonet, '97]**

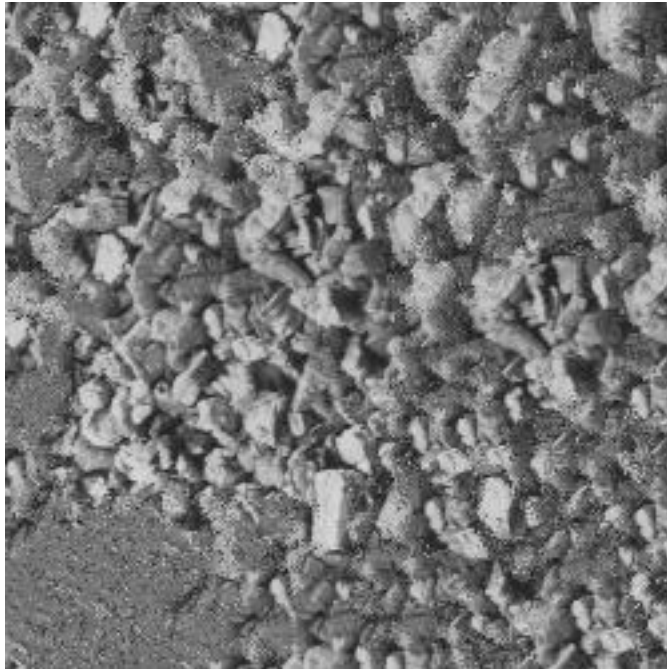
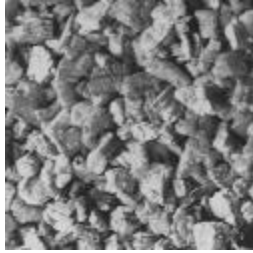


**Simple tiling**



**Our approach**

# Failure Cases



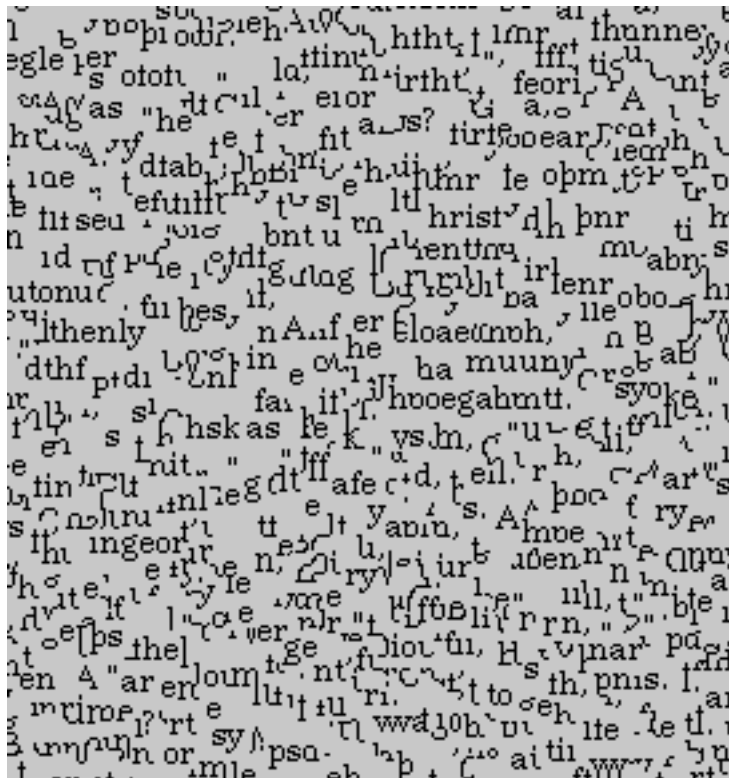
**Growing garbage**



**Verbatim copying**

# Homage to Shannon

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# Constrained Text Synthesis

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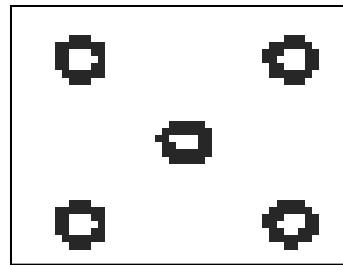
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# Applications

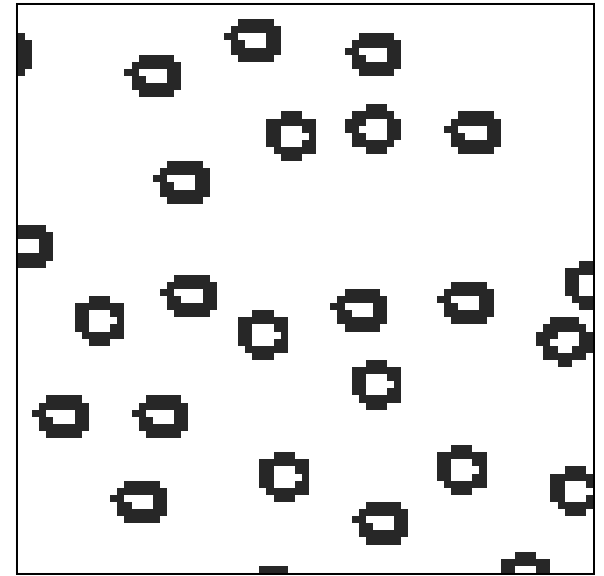
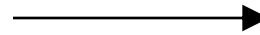
- Occlusion fill-in
  - for 3D reconstruction
- region-based image and video compression
  - a small sample of textured region is stored
- Texturing non-developable objects
  - growing texture directly on surface
- Motion synthesis

# Texturing a sphere

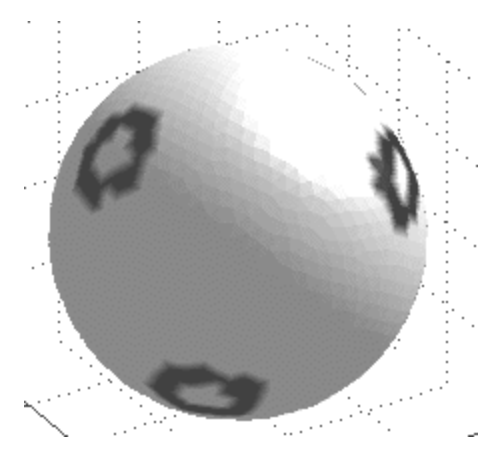
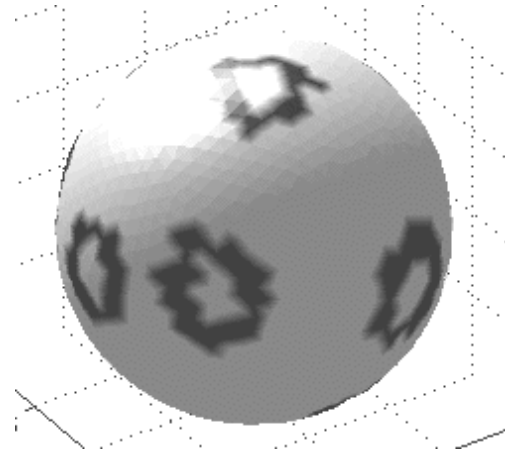
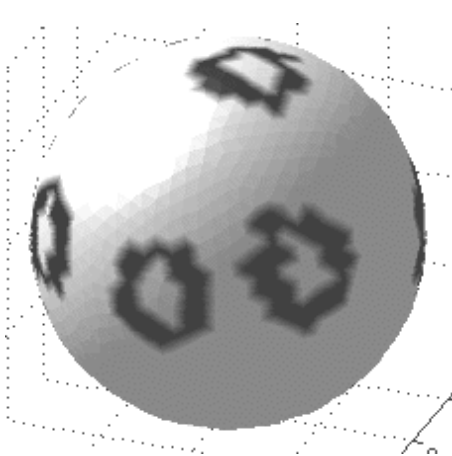
Sample image



2D



3D





# Image Extrapolation



# Summary

- Advantages:
  - conceptually simple
  - models a wide range of real-world textures
  - naturally does hole-filling
- Disadvantages:
  - it's greedy
  - it's slow
  - it's a heuristic
- Not an answer to texture analysis, but hopefully some inspiration!

# Acknowledgments

- Thanks to:
  - Alex Berg
  - Elizaveta Levina
  - Jitendra Malik
  - Yair Weiss
- Funding agencies
  - NSF Graduate Fellowship
  - Berkeley Fellowship
  - ONR MURI
  - California MIRCO

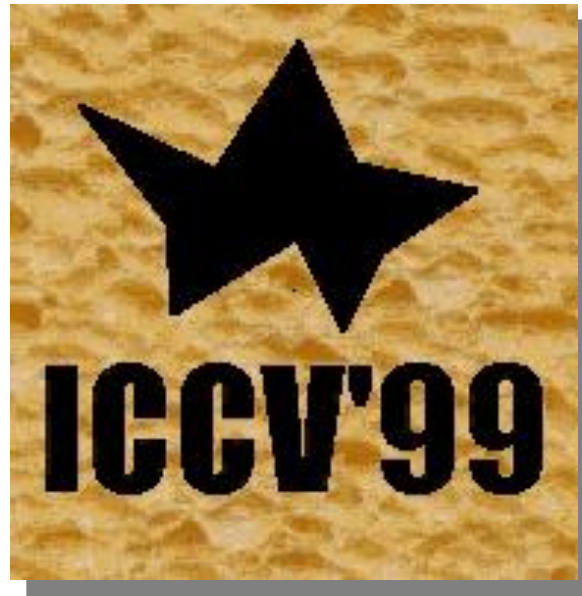








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