

# Texture Synthesis

## Bush campaign digitally altered TV ad

President Bush's campaign acknowledged Thursday that it had digitally altered a photo that appeared in a national cable television commercial. In the photo, a handful of soldiers were multiplied many times.

This section shows a sampling of the duplication of soldiers.

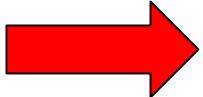


AP

Slides adapted from [Alyosha Efros](#)

# Texture

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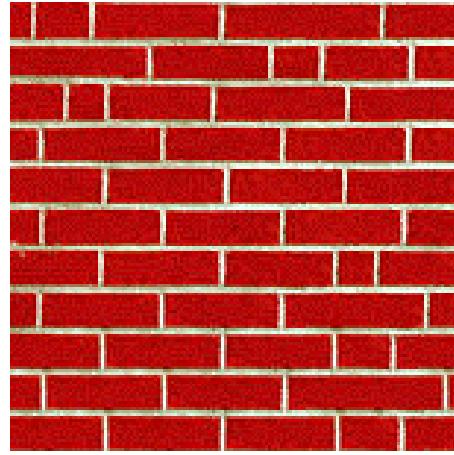
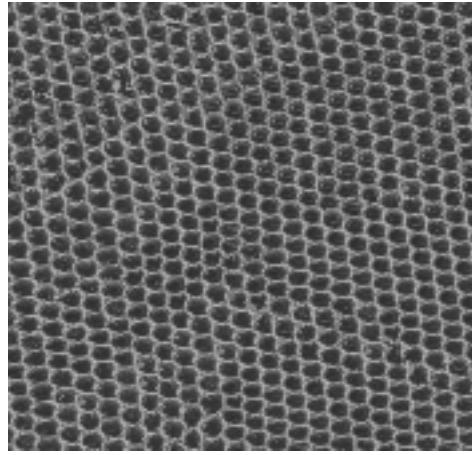


## Today's Reading

- [Alexei A. Efros](#) and [Thomas K. Leung](#), “Texture Synthesis by Non-parametric Sampling,” Proc. International Conference on Computer Vision (ICCV), 1999.
  - <http://www.cs.berkeley.edu/~efros/research/NPS/efros-iccv99.pdf>
- (supplementary) Forsythe Chapter 9

# Modeling Texture

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What is texture?

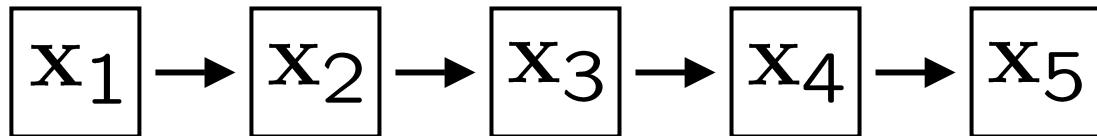
How can we model it?

# Markov Chains

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## Markov Chain

- a sequence of random variables  $\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_n$
- $\mathbf{x}_t$  is the **state** of the model at time t



- **Markov assumption:** each state is dependent only on the previous one
  - dependency given by a **conditional probability**:

$$p(\mathbf{x}_t | \mathbf{x}_{t-1})$$

- The above is actually a *first-order* Markov chain
- An *N'th-order* Markov chain:

$$p(\mathbf{x}_t | \mathbf{x}_{t-1}, \dots, \mathbf{x}_{t-N})$$

# Markov Chain Example: Text

“A dog is a man’s best friend. It’s a dog eat dog world out there.”

$\mathbf{x}_{t-1}$

a		$2/3$		$1/3$								
dog			$1/3$				$1/3$	$1/3$				
is	1											
man’s					1							
best						1						
friend							1					1
it’s	1											
eat		1										
world									1			
out										1		
there											1	
.												.
	a	dog	is	man’s	best	friend	it’s	eat	world	out	there	$\mathbf{x}_t$

$p(\mathbf{x}_t | \mathbf{x}_{t-1})$

# Text synthesis

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Create plausible looking poetry, love letters, term papers, etc.

## Most basic algorithm

1. Build probability histogram
  - find all blocks of  $N$  consecutive words/letters in training documents
  - compute probability of occurrence  $p(\mathbf{x}_t | \mathbf{x}_{t-1}, \dots, \mathbf{x}_{t-(n-1)})$
2. Given words  $\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_{k-1}$ 
  - compute  $\mathbf{x}_k$  by sampling from  $p(\mathbf{x}_t | \mathbf{x}_{t-1}, \dots, \mathbf{x}_{t-(n-1)})$

[Scientific American, June 1989, Dewdney]

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“I Spent an Interesting Evening Recently with a Grain of Salt”

- Mark V. Shaney

(computer-generated contributor to UseNet News group called net.singles)

Output of 2nd order word-level Markov Chain after training on 90,000 word philosophical essay:

*“Perhaps only the allegory of simulation is unendurable--more cruel than Artaud's Theatre of Cruelty, which was the first to practice deterrence, abstraction, disconnection, deterritorialisation, etc.; and if it were our own past. We are witnessing the end of the negative form. But nothing separates one pole from the very swing of voting "rights" to electoral...”*

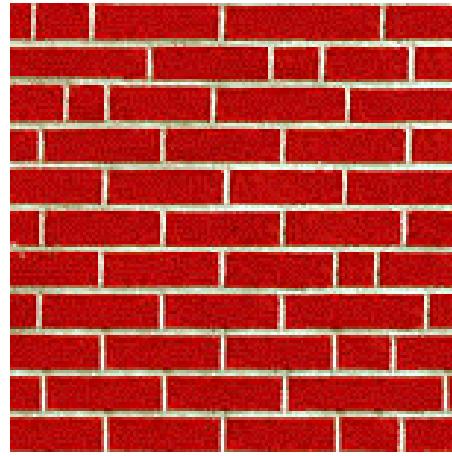
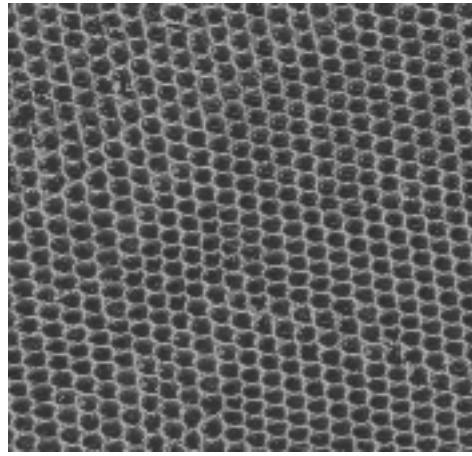
# An Automatic Paper Generator

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<http://pdos.csail.mit.edu/scigen/>

# Modeling Texture

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## What is texture?

- An image obeying some statistical properties
- Similar structures repeated over and over again
- Often has some degree of randomness

# Markov Random Field

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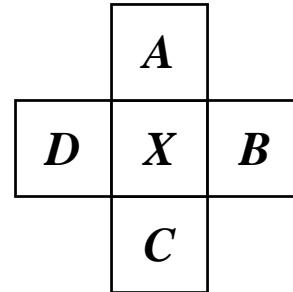
## A Markov random field (MRF)

- generalization of Markov chains to two or more dimensions.

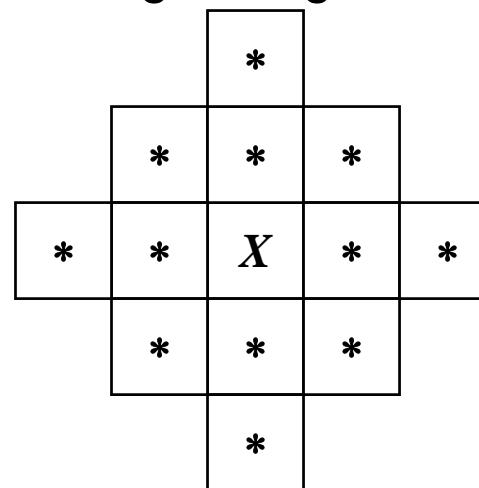
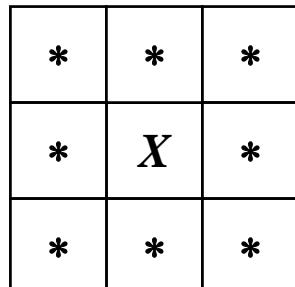
### First-order MRF:

- probability that pixel  $X$  takes a certain value given the values of neighbors  $A, B, C$ , and  $D$ :

$$P(X|A, B, C, D)$$



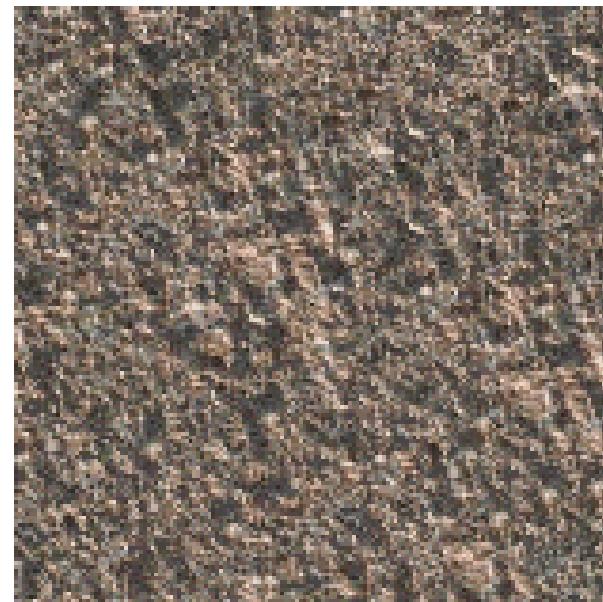
- Higher order MRF's have larger neighborhoods



# Texture Synthesis [\[Efros & Leung, ICCV 99\]](#)

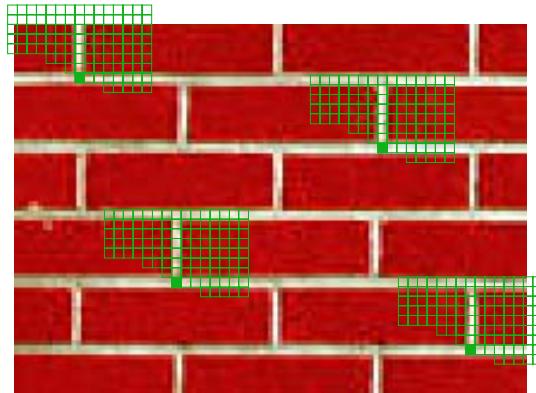
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Can apply 2D version of text synthesis

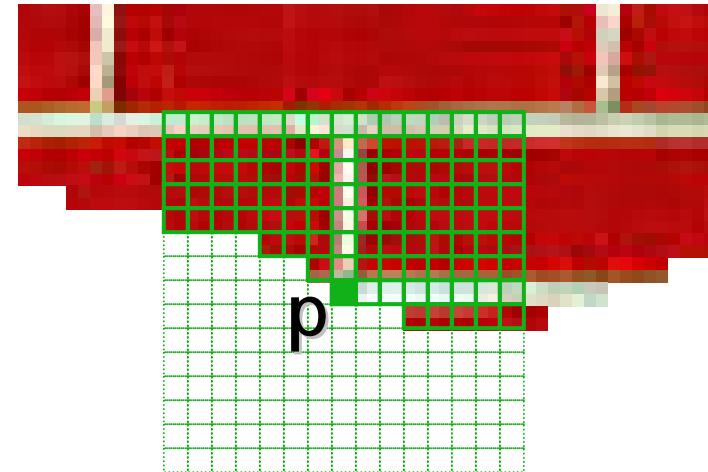


# Synthesizing One Pixel

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input image

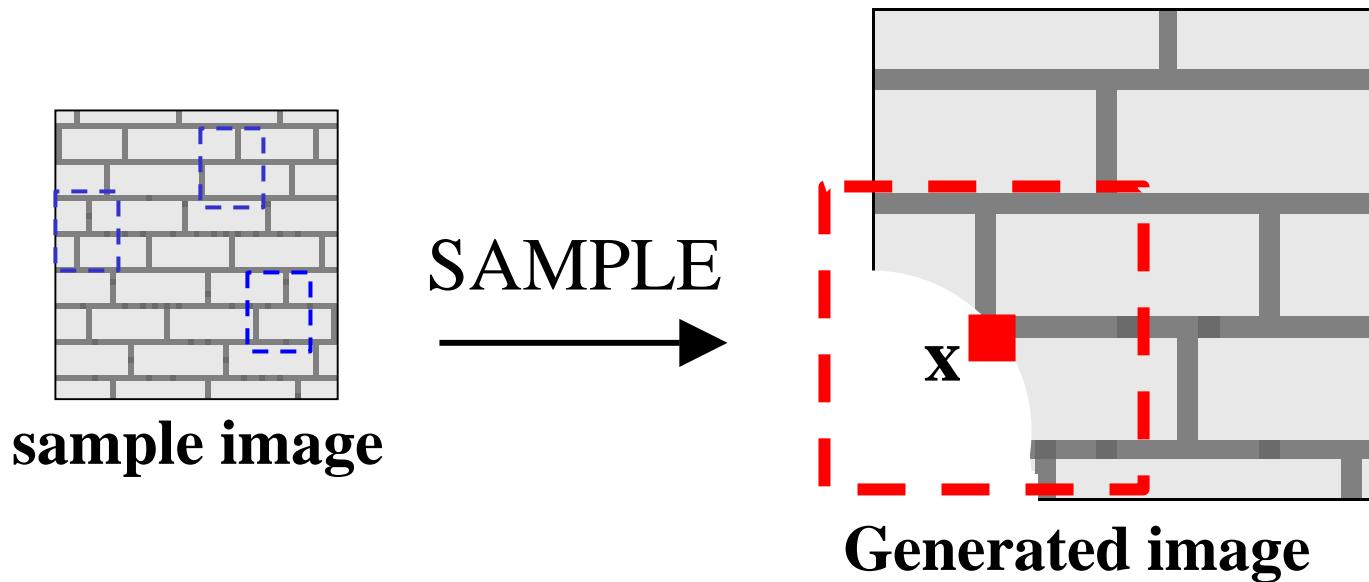


synthesized image

- What is  $P(x|\text{neighborhood of pixels around } x)$  ?
- Find all the windows in the image that match the neighborhood
  - consider only pixels in the neighborhood that are already filled in
- To synthesize  $x$ 
  - pick one matching window at random
  - assign  $x$  to be the center pixel of that window

# Really Synthesizing One Pixel

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- An exact neighbourhood match might not be present
- So we find the **best** matches using SSD error and randomly choose between them, preferring better matches with higher probability

# Growing Texture

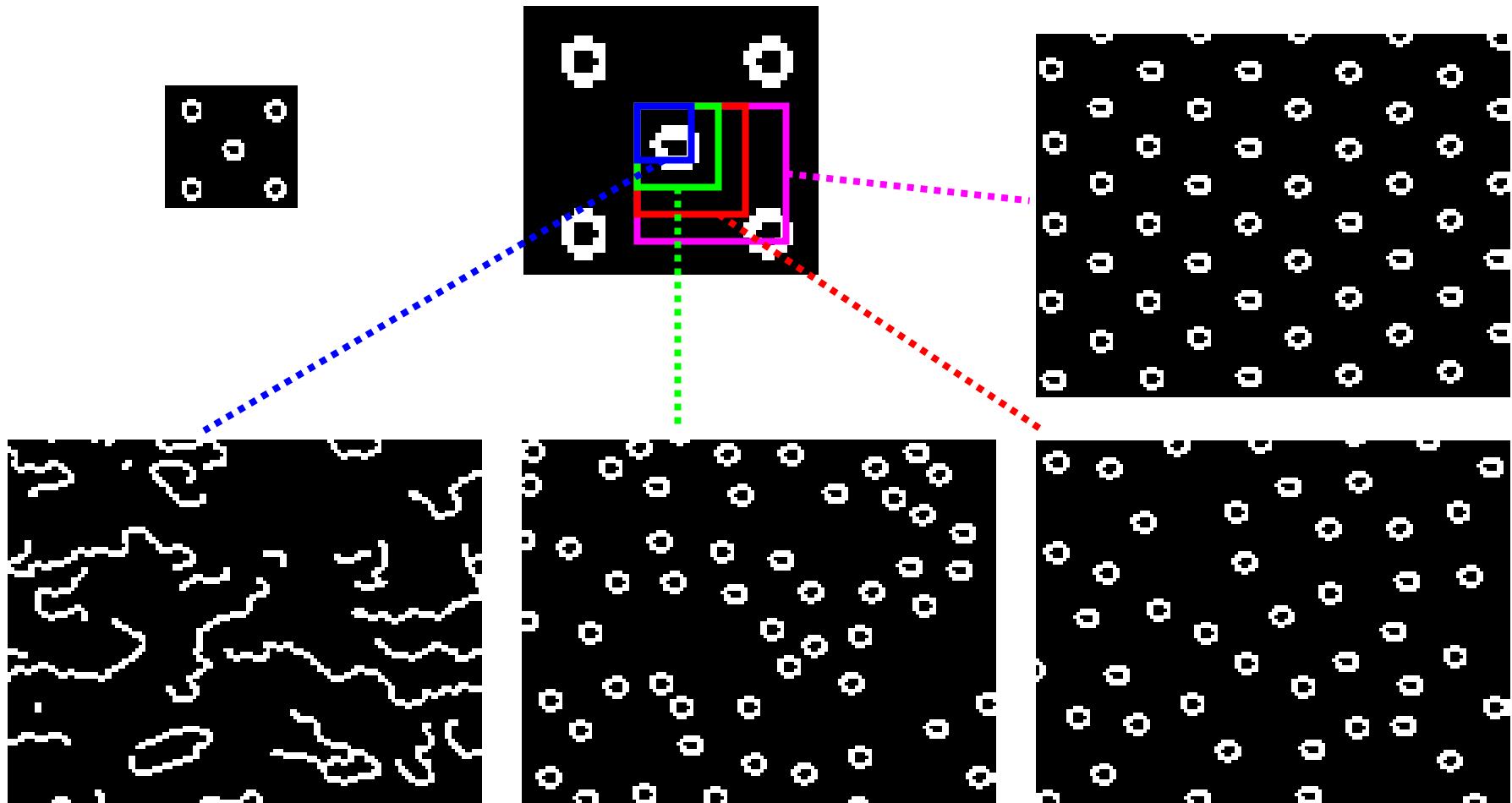
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- Starting from the initial image, “grow” the texture one pixel at a time

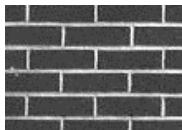
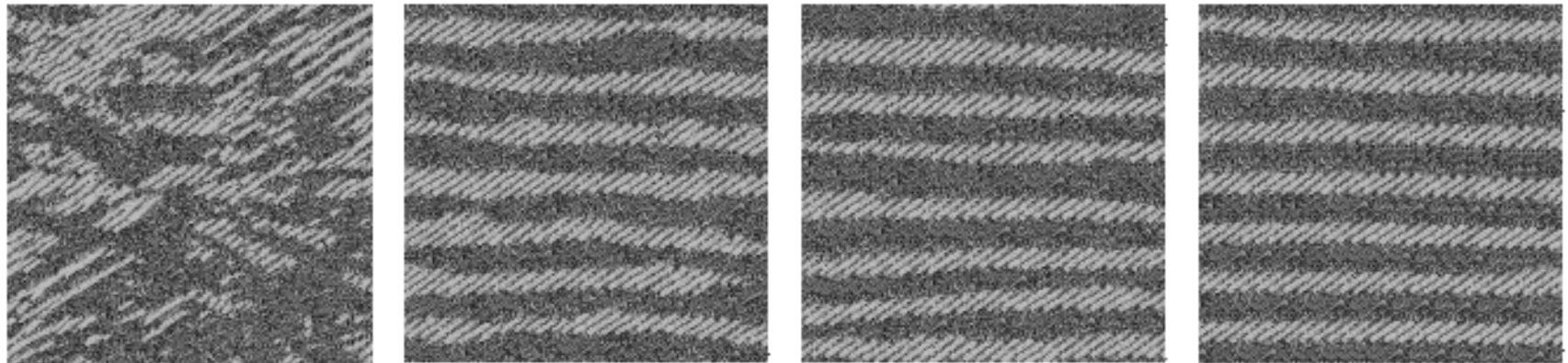
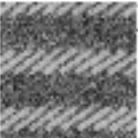
# Window Size Controls Regularity

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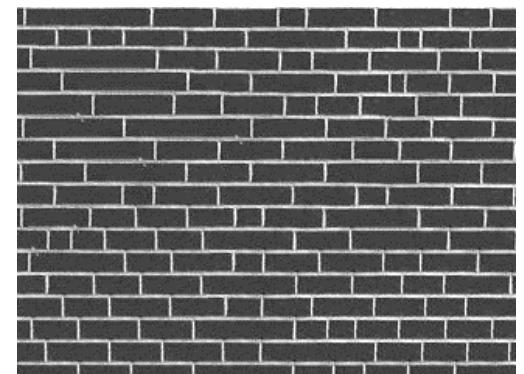
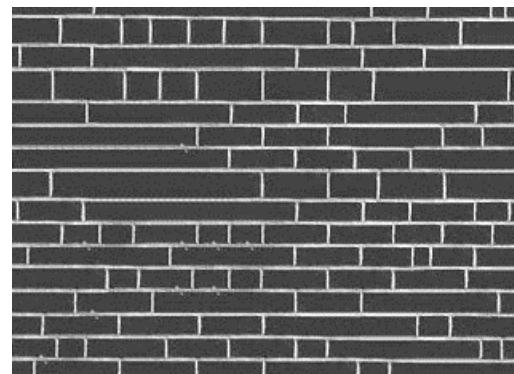
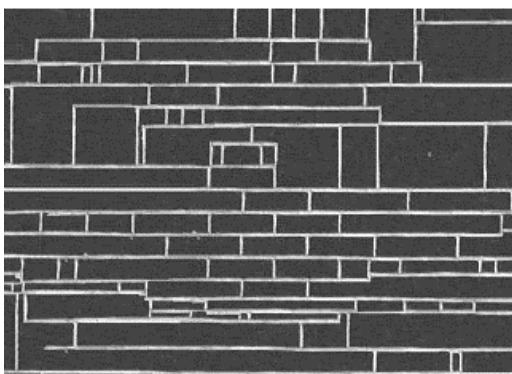


# More Synthesis Results

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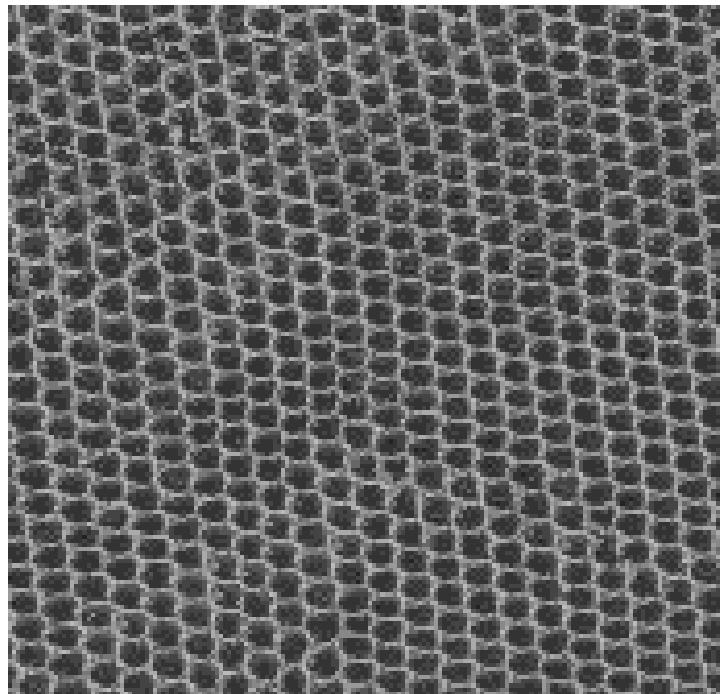
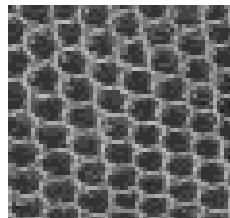
Increasing window size



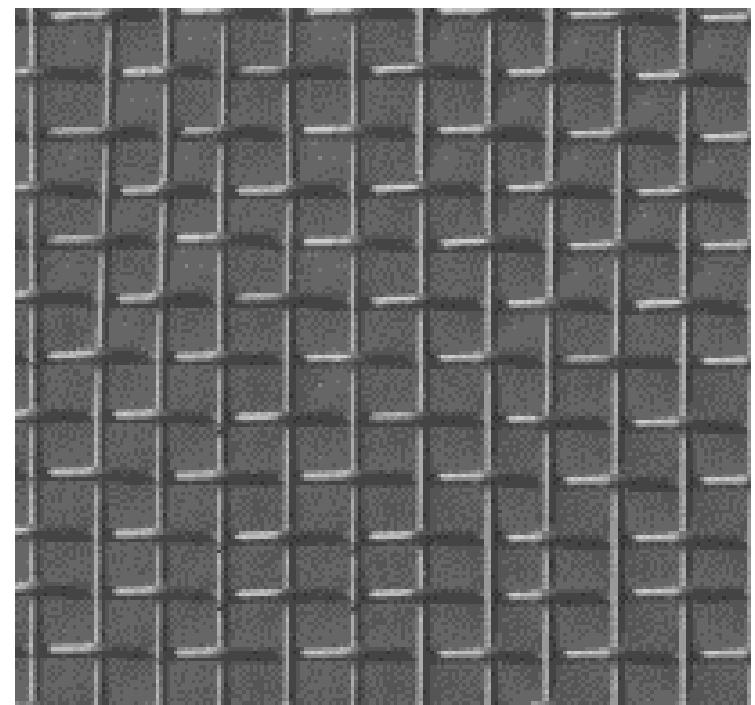
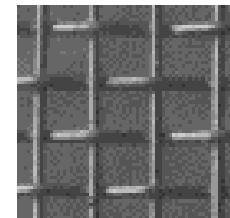
# More Results

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reptile skin

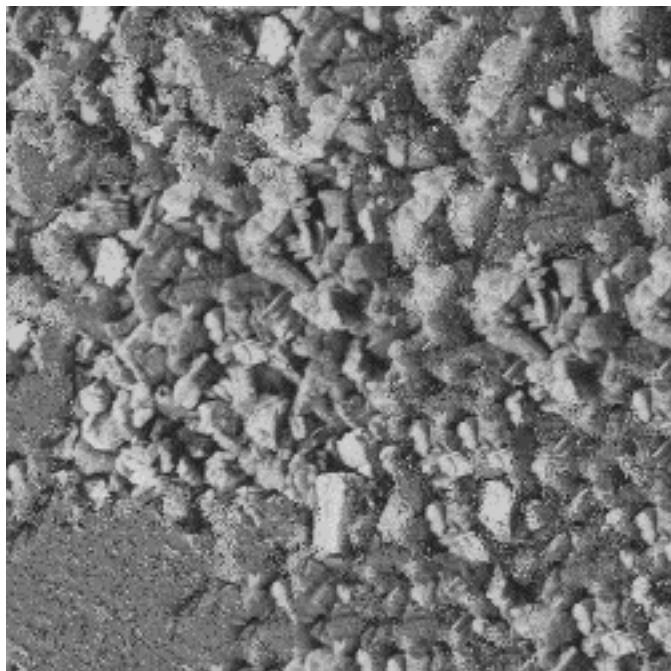
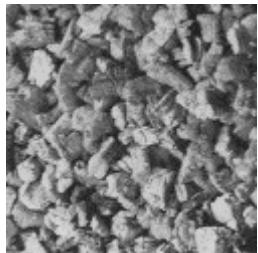


aluminum wire



# Failure Cases

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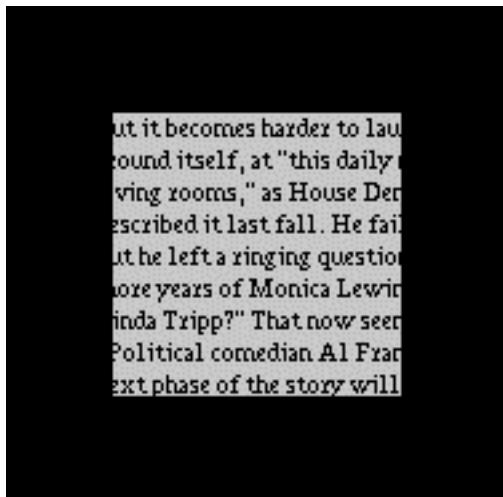


**Growing garbage**

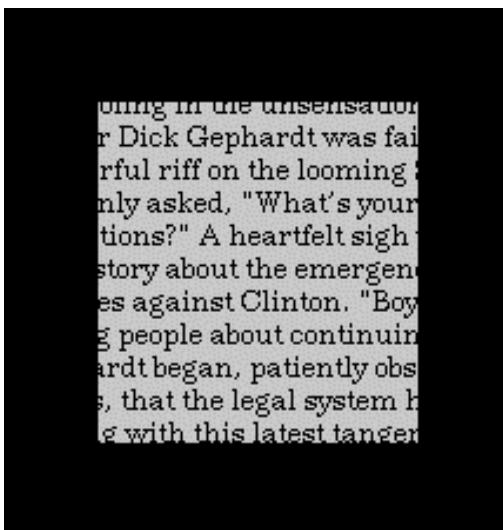


**Verbatim copying**

# Image-Based Text Synthesis



ut it becomes harder to laud  
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ut he left a ringing question  
ore years of Monica Lewin  
inda Tripp?" That now seen  
Political comedian Al Fran  
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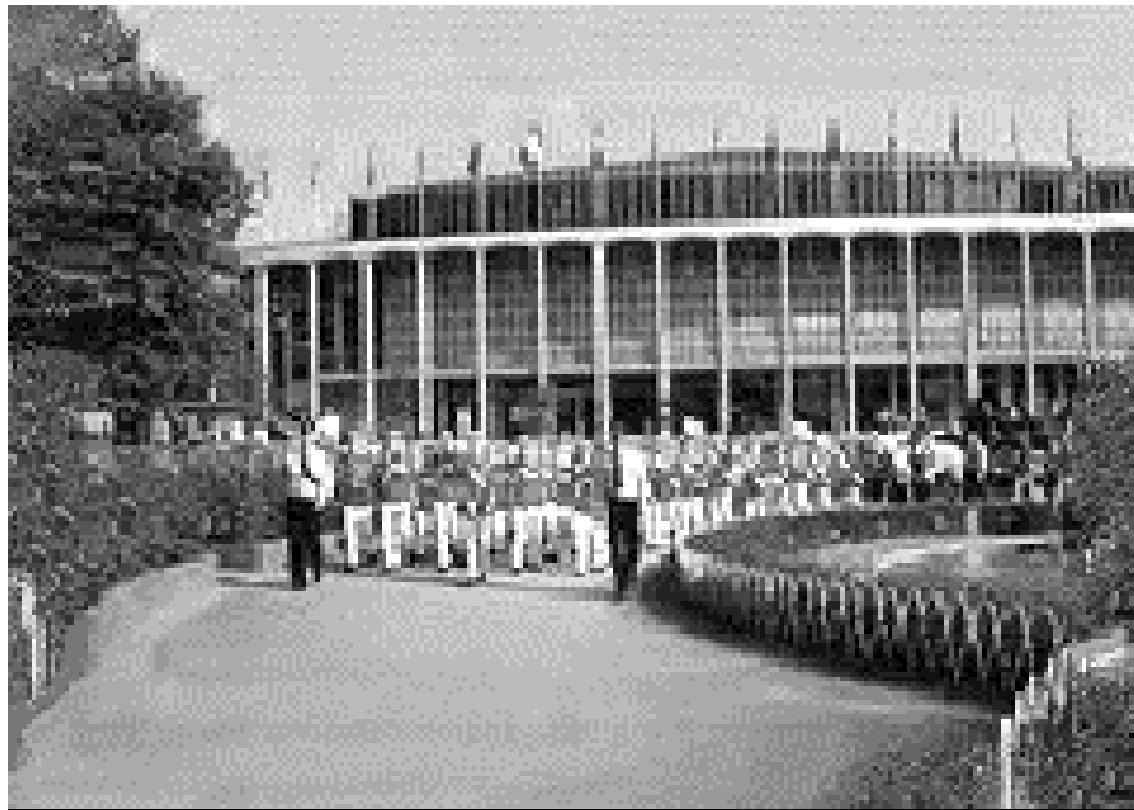


af as t e p r o v o u y d v i t a i n n i c a t i  
t o l i k b i r b l e v c p P b p s p y a i h  
u v e s t i h g i n t h e t i n s e n s a t i o n i b e t  
r Dick Gephardt was faiem  
s w l o o r f u l r i f f o n t h e l o o m i n g i s  
as t o n l y a s k e d "W h a t ' s y o u r f e l t s i g  
r u r e n t i o n s ? " A h e a r t f e l t s i g h t v a t i  
s o o c u e s t o r y a b o u t t h e e m e r g e n e n u t i  
t c u l l e s a g a i n s t C l i n t o n " B o y o a t e l l u  
u i v t i g p e o p l e a b o u t c o n t i n u i n g v a t i  
u r n g a r d t b e g a n p a t i e n t l y o b s t i  
u a m s t h a t t h e l e g a l s y s t e m h u r t i  
u t h a g w i t h t h i s l a t e s t t a n g e r v i f i  
u y i a t i l l i j i r a v h a f h f u r i a t  
u d d a r e o s ? h a t i m i n i u v i  
u h o s e a r e o s ? u t e i f u i v i  
u s l i l R u i e l s u s e s t h u i v i  
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11He years od itself, at hizipp?" Thes haroedat  
ipp?" Tripp?"s coms," ars ol come f, at "that nd  
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roed itse round itself, at "this daily nd itsel of  
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# Extrapolation

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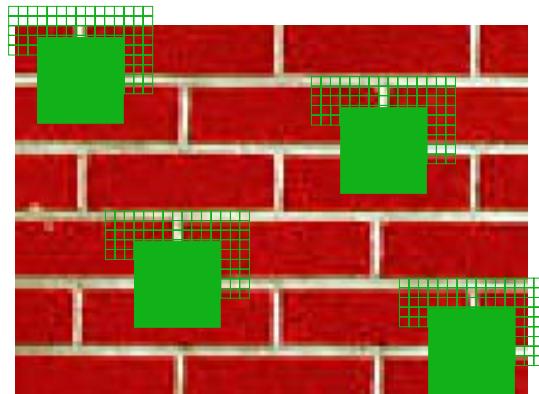
# Speed

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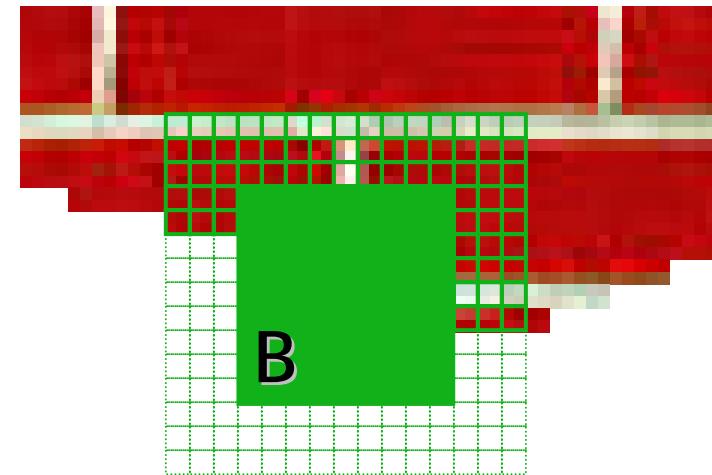
- Given: image of  $k^2$  pixels
- Output: image of  $n^2$  pixels
- how many window comparisons does this algorithm require?

# Block-based texture synthesis

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Input image



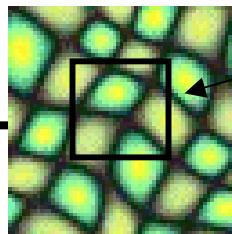
Synthesizing a block

Observation: neighbor pixels are highly correlated

Idea: unit of synthesis = block

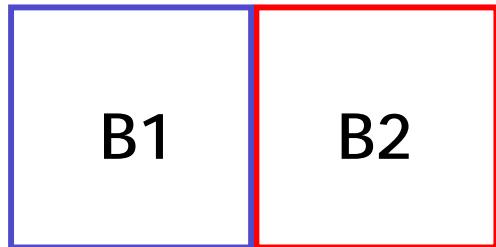
- Exactly the same but now we want  $P(B|N(B))$
- Much faster: synthesize all pixels in a block at once

[Image Quilting for Texture Synthesis and Transfer](#), Efros & Freeman, SIGGRAPH, 2001.

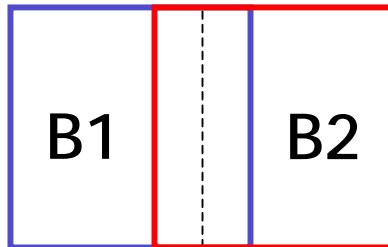


block

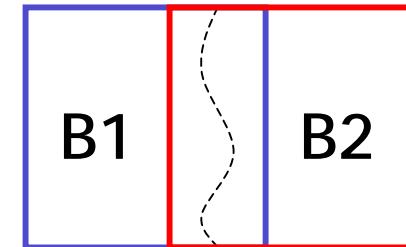
Input texture



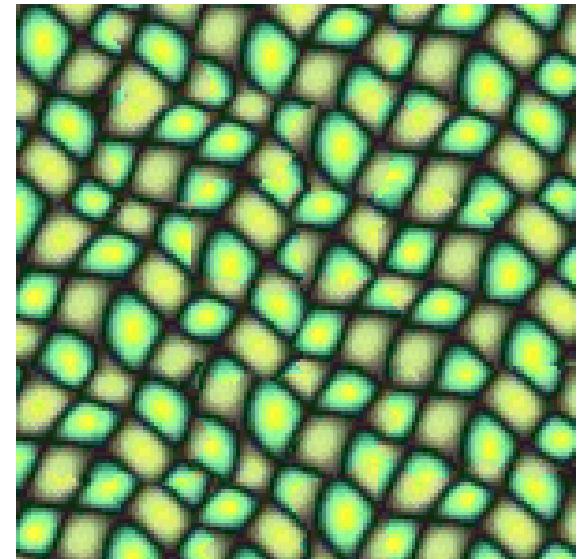
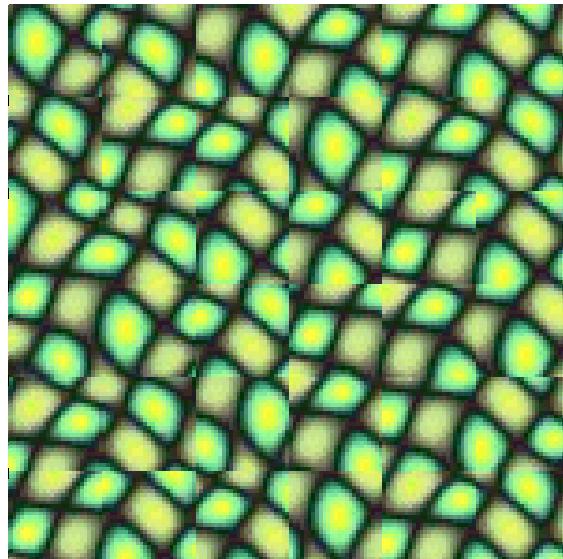
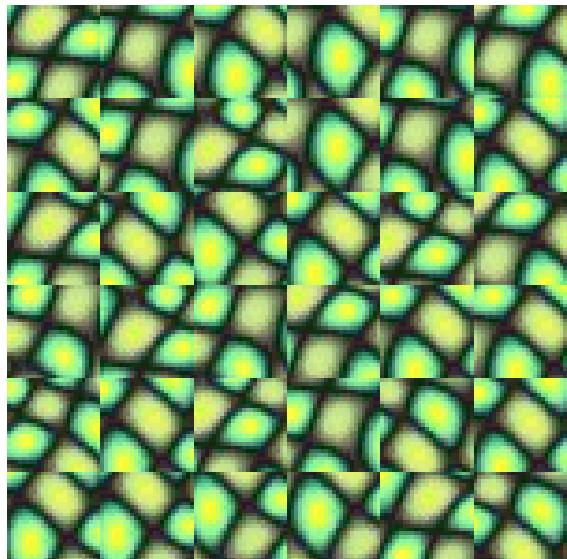
Random placement  
of blocks



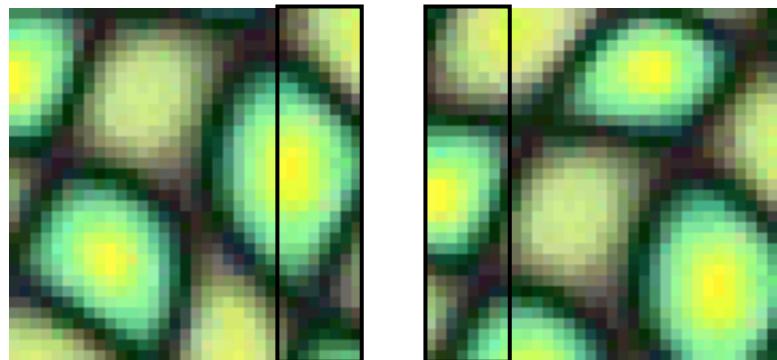
Neighboring blocks  
constrained by overlap



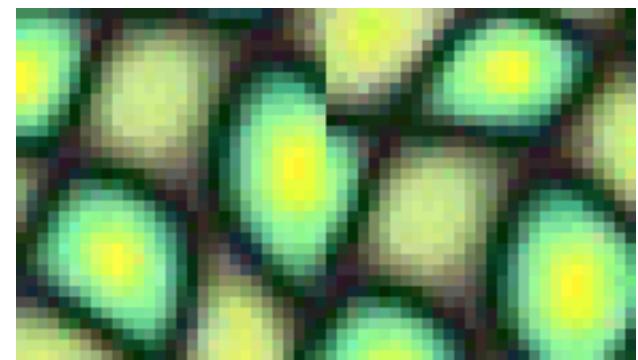
Minimal error  
boundary cut



overlapping blocks



vertical boundary

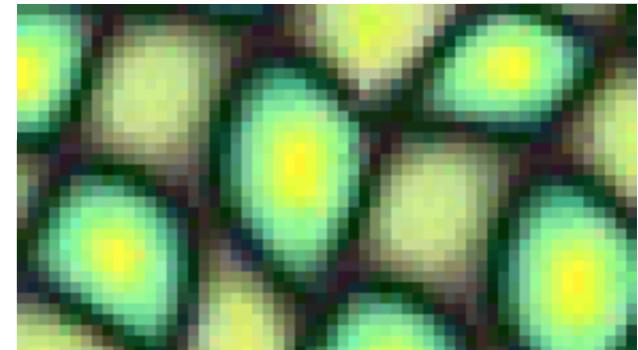


$$\left[ \begin{array}{c} \text{block 1} \\ - \\ \text{block 2} \end{array} \right]^2 = \text{overlap error}$$

Diagram illustrating the calculation of overlap error. Two overlapping blocks are shown, and their difference is squared to produce a heatmap of the overlap error. The error is localized to the overlapping region, shown as a red line.

overlap error

min. error boundary



# Fill Order

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In what order should we fill the pixels?

# Fill Order

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In what order should we fill the pixels?

- choose pixels that have more neighbors filled
- choose pixels that are continuations of lines/curves/edges

# More on Image Inpainting

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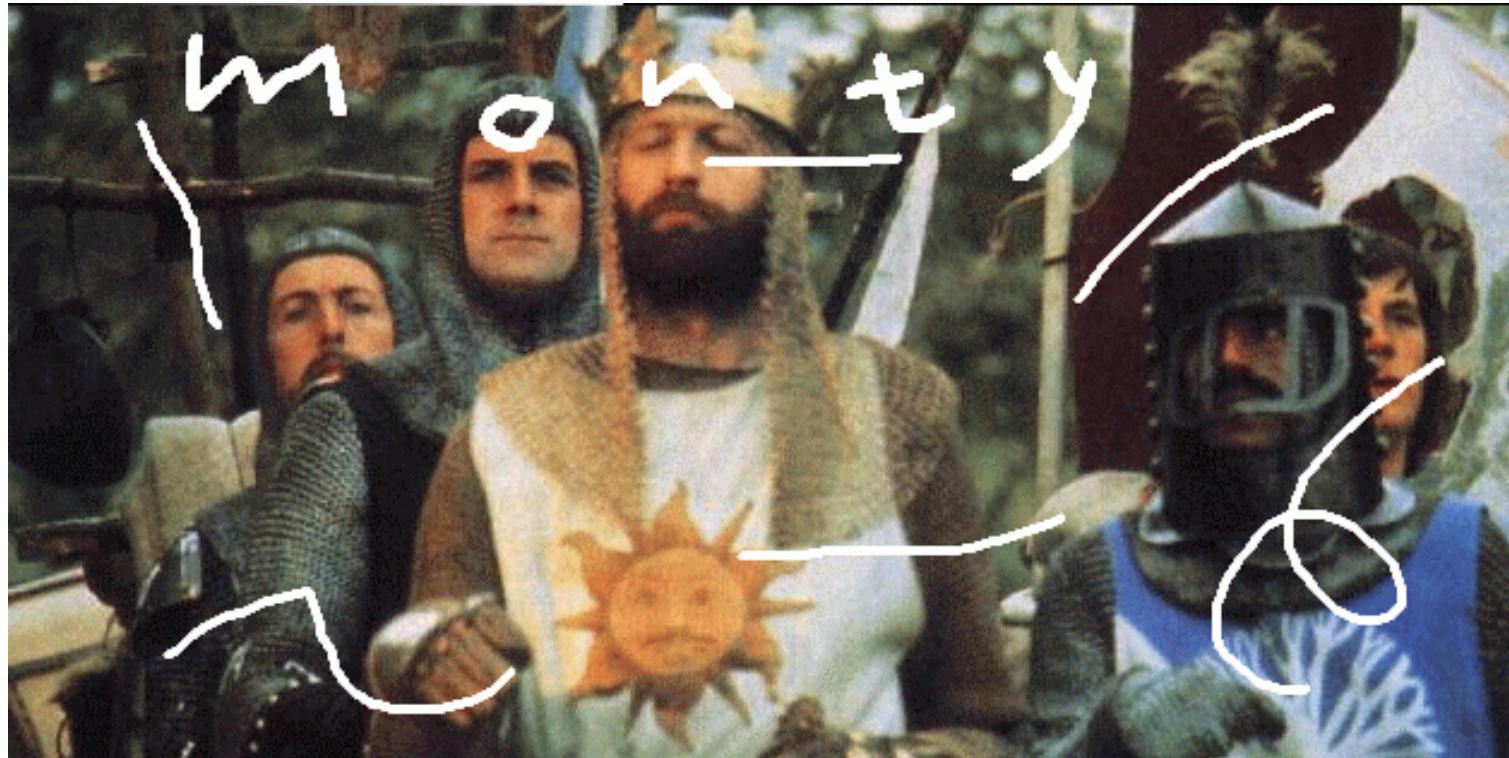
Can also be formulated as image diffusion

Idea of propagating along lines comes from

- Bertalmío, Sapiro, Caselles, and Ballester, “[Image Inpainting](#),” Proc. SIGGRAPH 2000.

# Image Inpainting

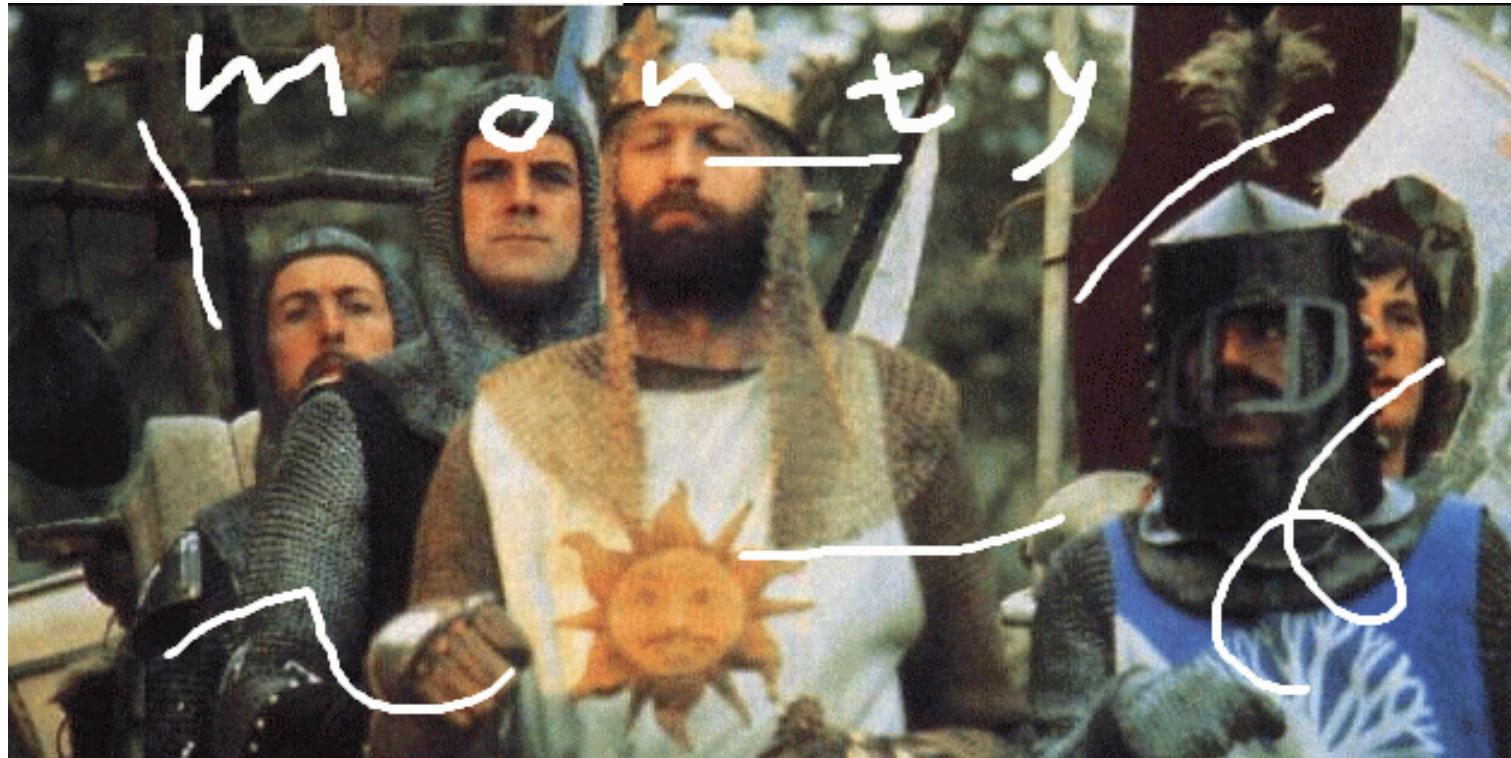
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*Image Inpainting*, M. Bertalmío et al.  
<http://www.iua.upf.es/~mbertalmio//restoration.html>

# Image Inpainting

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*Image Inpainting*, M. Bertalmío et al.  
<http://www.iua.upf.es/~mbertalmio//restoration.html>

# Image Inpainting

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*Image Inpainting*, M. Bertalmío et al.  
<http://www.iua.upf.es/~mbertalmio//restoration.html>

# Texture Transfer [Efros & Freeman 2001]

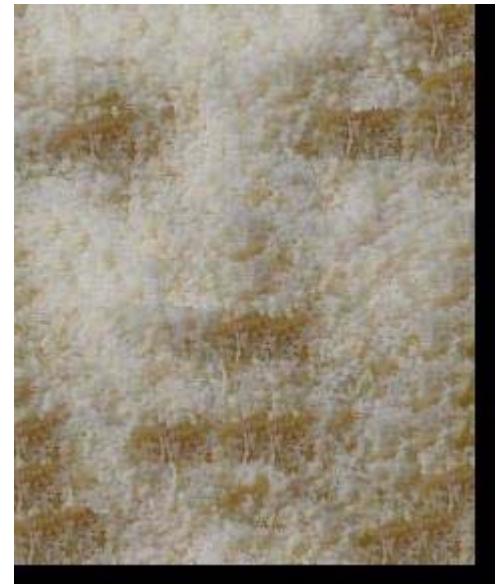
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Constraint



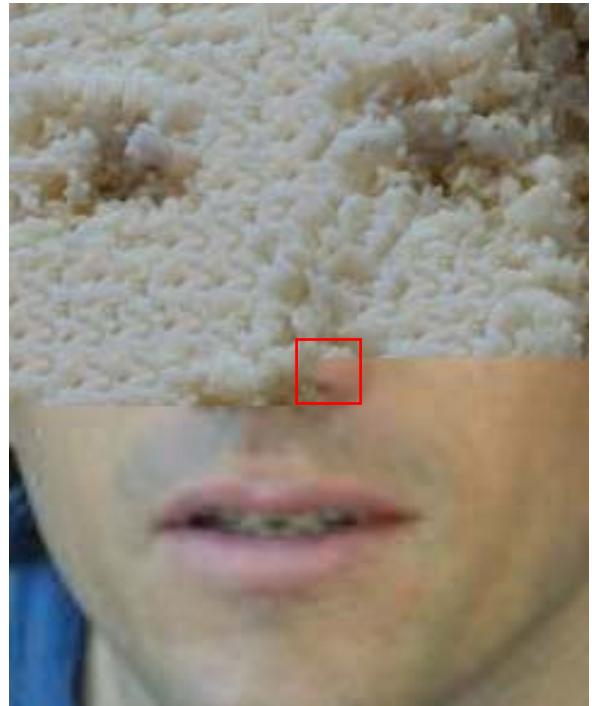
Texture sample



# Texture Transfer

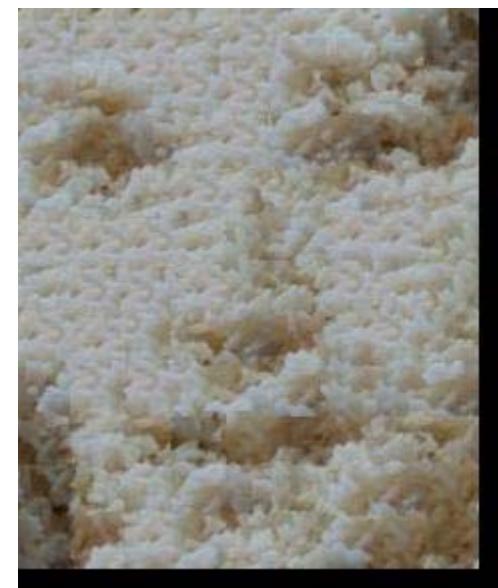
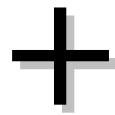
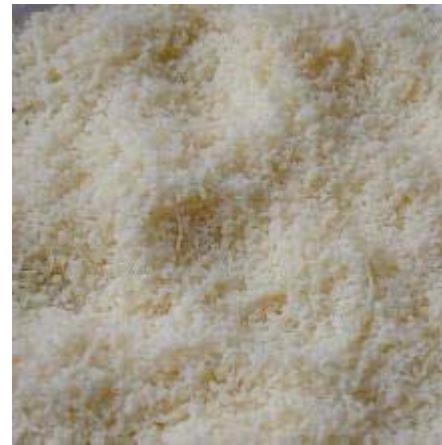
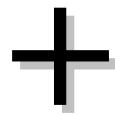
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Take the texture from one image and “paint” it onto another object



Same algorithm as before with additional term

- do texture synthesis on image1, create new image (size of image2)
- add term to match intensity of image2



rice

# Image repairing (Jia and Tang, '03)

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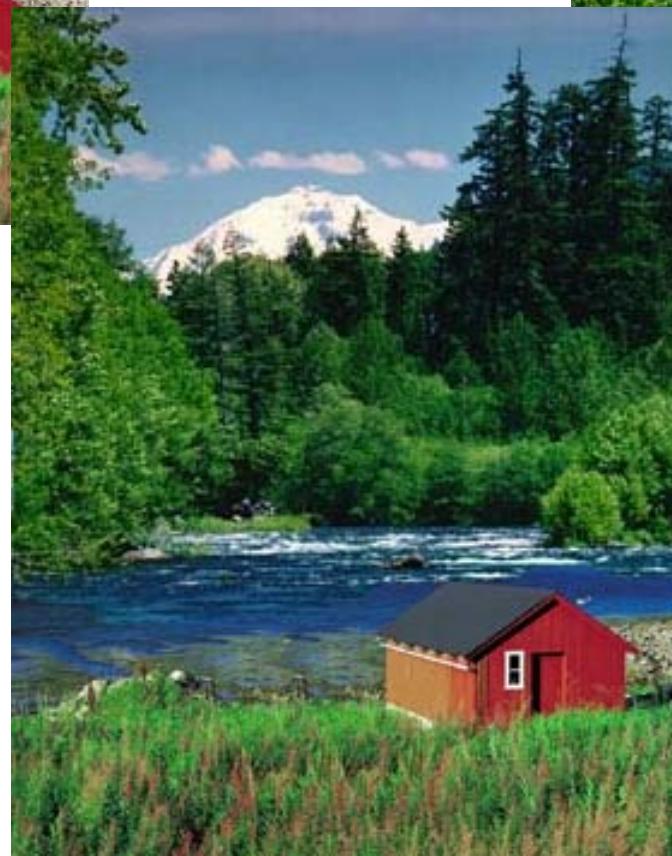


# Combining two images

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[Graphcut Textures, Kwatra et al., SIGGRAPH 2003.](#)



# Graph cut setup

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# Image Analogies (Hertzmann '01)

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A



A'



B



B'

# Artistic Filters

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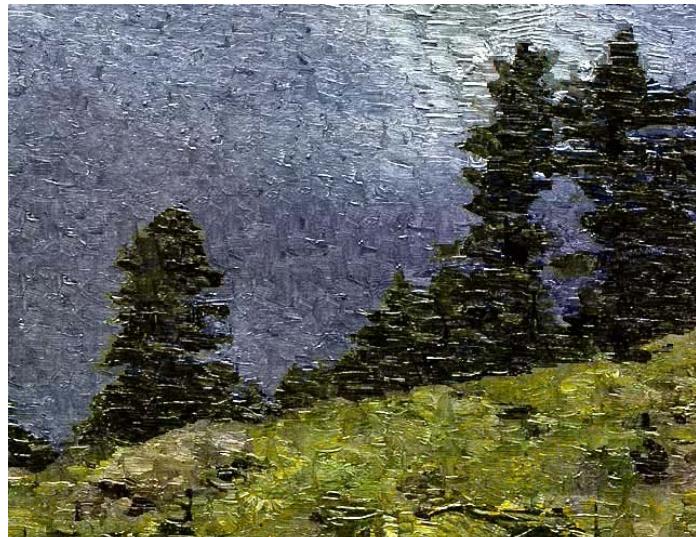
A



A'



B



B'

# Texture-by-numbers

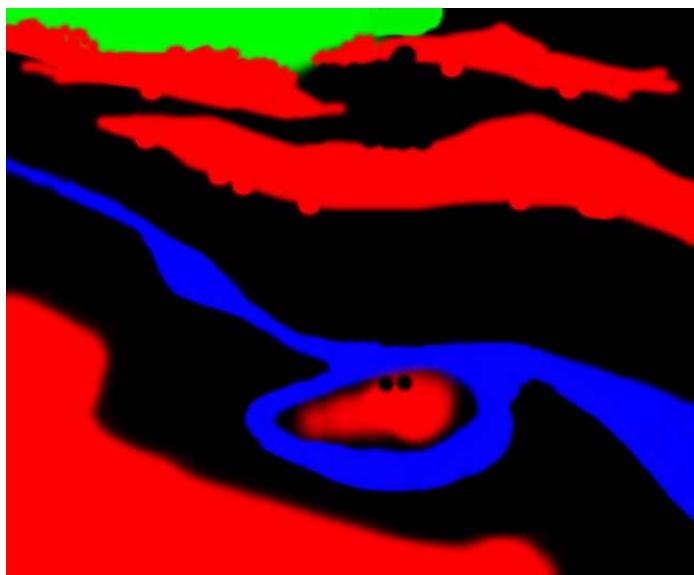
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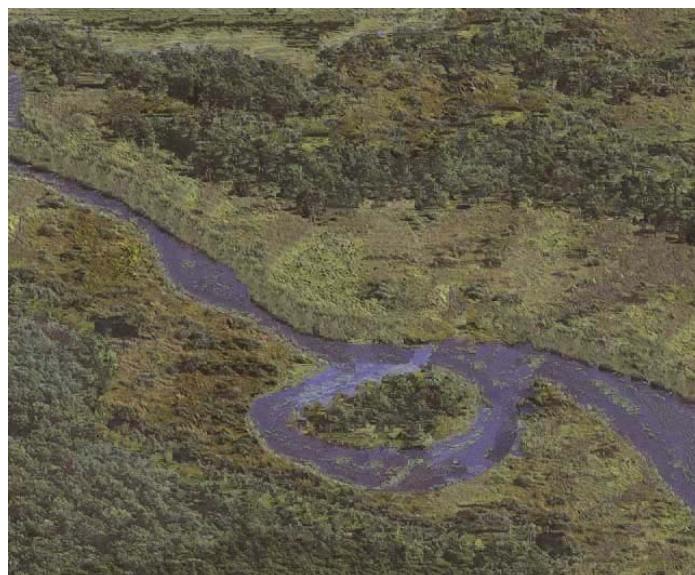
A



A'



B



B'

# Colorization

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A



B



A'



B'

# References

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- Efros and Leung, “[Texture Synthesis by Non-parametric Sampling](#),” Proc. ICCV, 1999.
- Efros and Freeman, “[Image Quilting for Texture Synthesis and Transfer](#),” Proc. SIGGRAPH 2001.
- Bertalmío, Sapiro, Caselles, and Ballester, “[Image Inpainting](#),” Proc. SIGGRAPH 2000.
- Jia and Tang. “[Image Repairing: a Robust Image Synthesis Technique by Adaptive ND Tensor Voting](#),” CVPR, 2003.
- Criminisi, Perez, and Toyama. “[Object Removal by Exemplar-based Inpainting](#),” Proc. CVPR, 2003.
- Kwatra, Schödl, Essa, Turk, and Bobick, “[Graphcut Textures: Image and Video Synthesis Using Graph Cuts](#),” Proc. SIGGRAPH 2003.
- Hertzmann, Jacobs, Oliver, Curless, and Salesin, “[Image Analogies](#),” Proc. SIGGRAPH 2001.