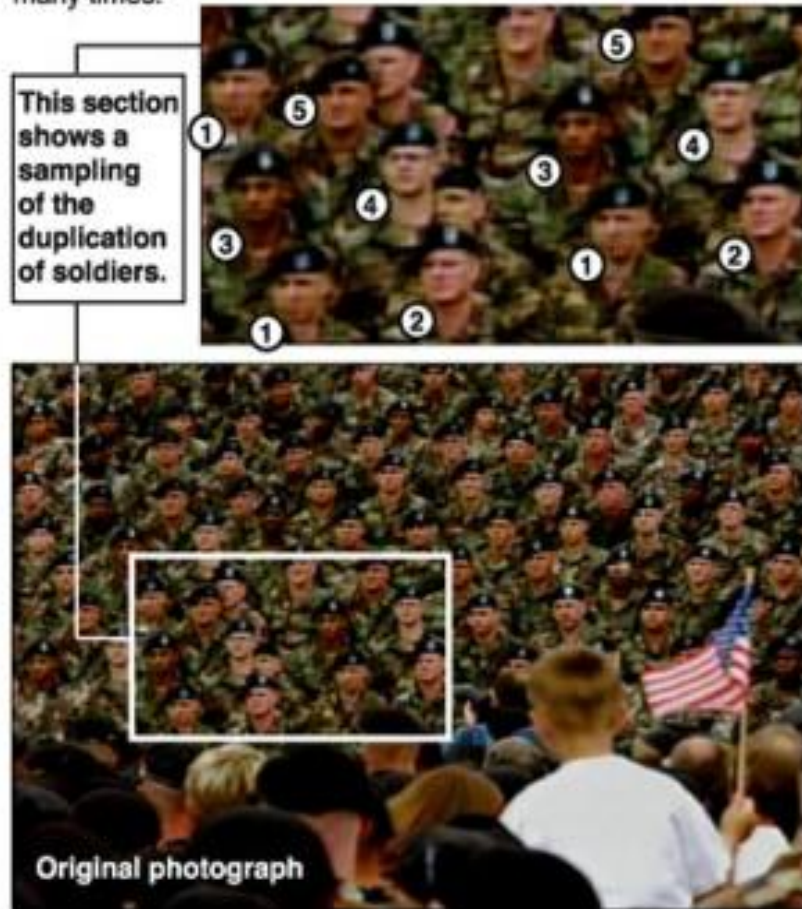


# Texture Synthesis

## 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.



AP

Slides adapted from [Alyosha Efros](#)

# Texture

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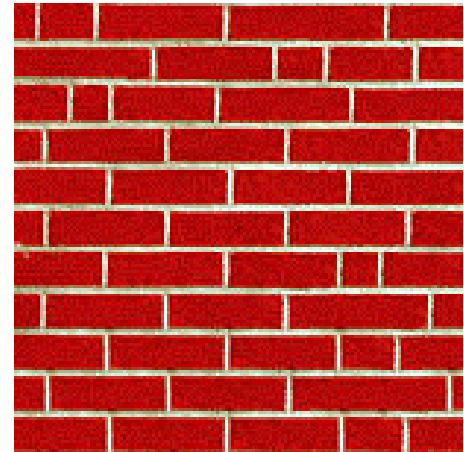
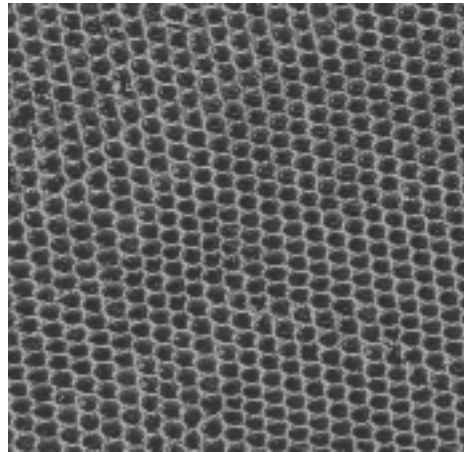
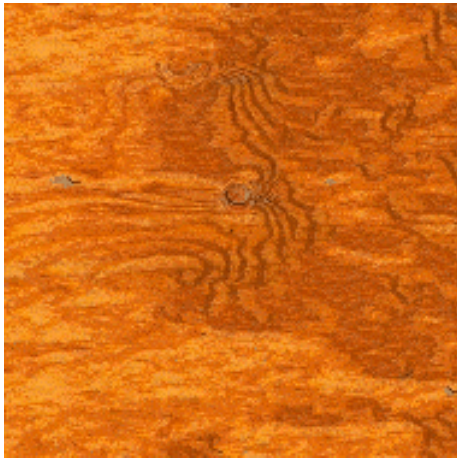


## Today's Reading

- [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

---



What is texture?

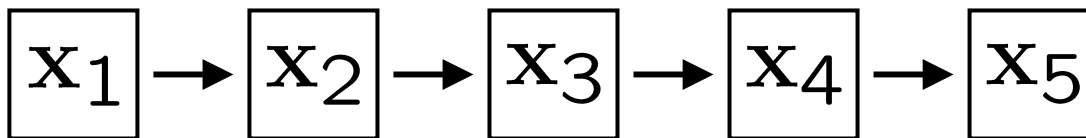
How can we model it?

# 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
it’s	1											
eat		1										
world										1		
out											1	
there												1
.							1					

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

$\mathbf{x}_t$

a dog is man’s best friend it’s eat world out there .

# Text synthesis

---

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

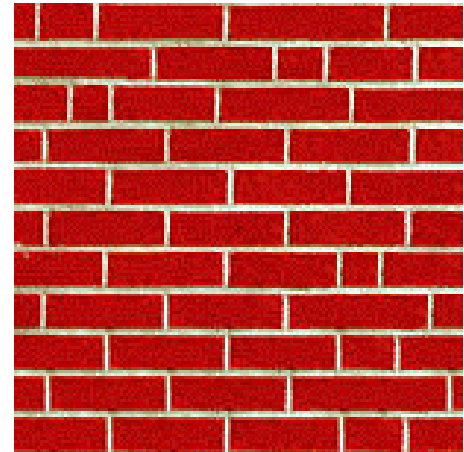
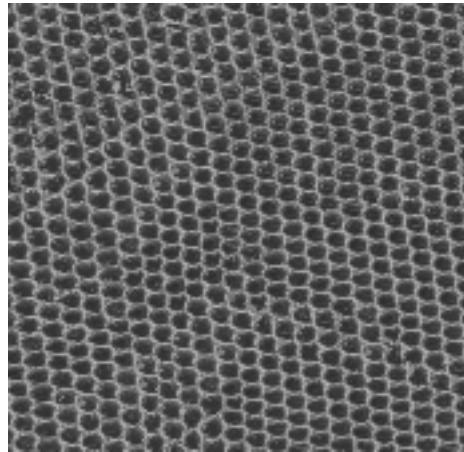
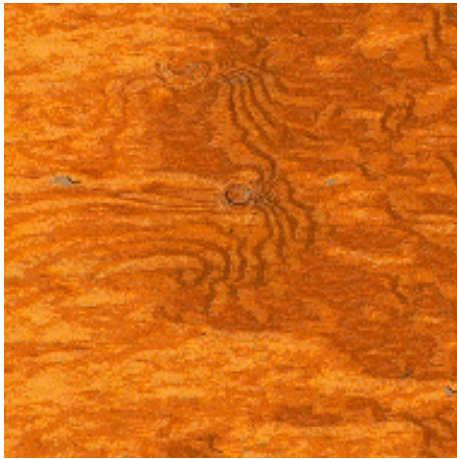
---

<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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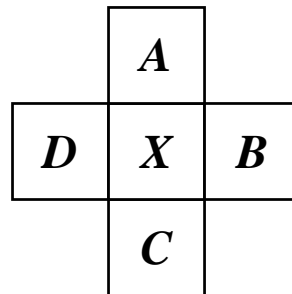
## A Markov random field (MRF)

- generalization of Markov chains to two or more dimensions.

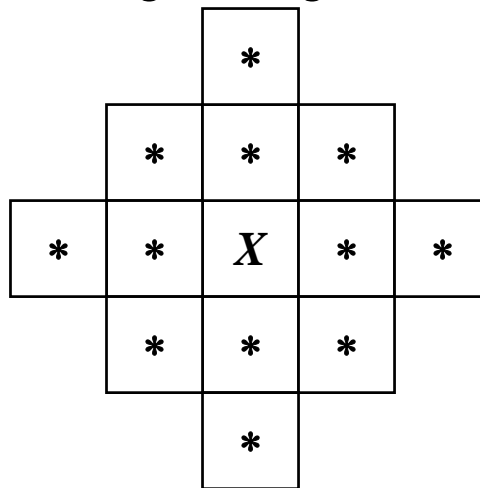
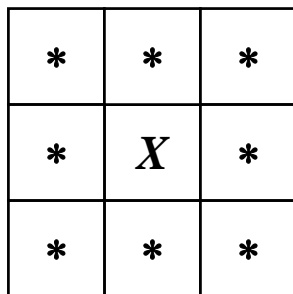
### First-order MRF:

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

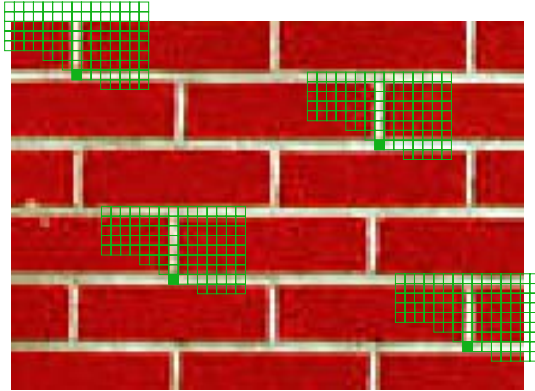
---

Can apply 2D version of text synthesis

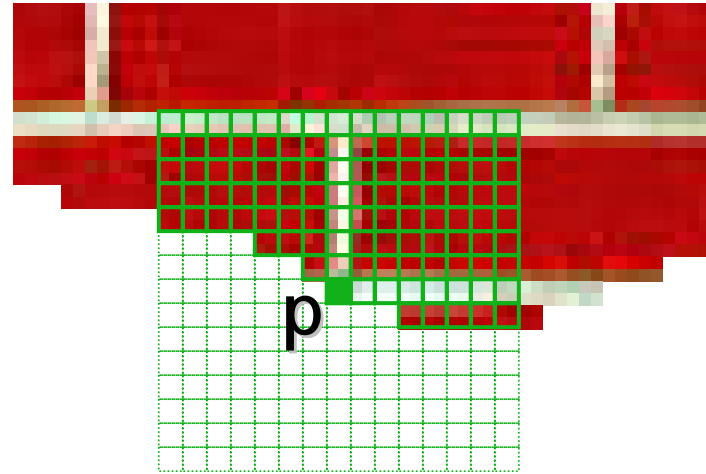


# Synthesizing One Pixel

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input image

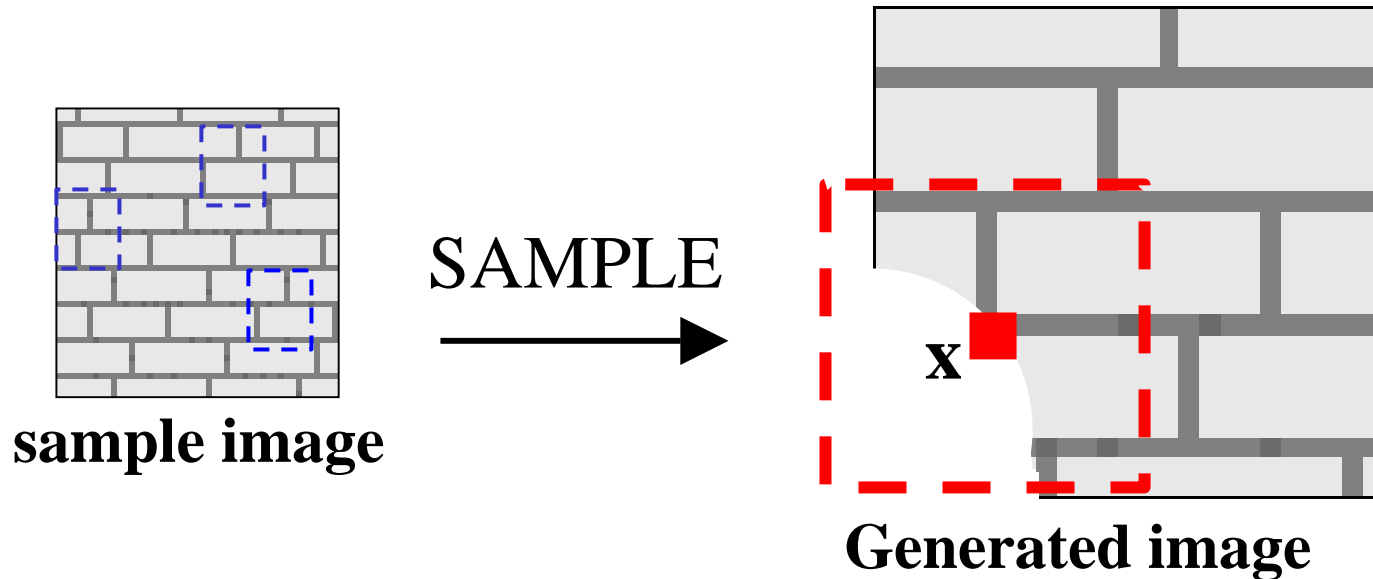


synthesized image

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

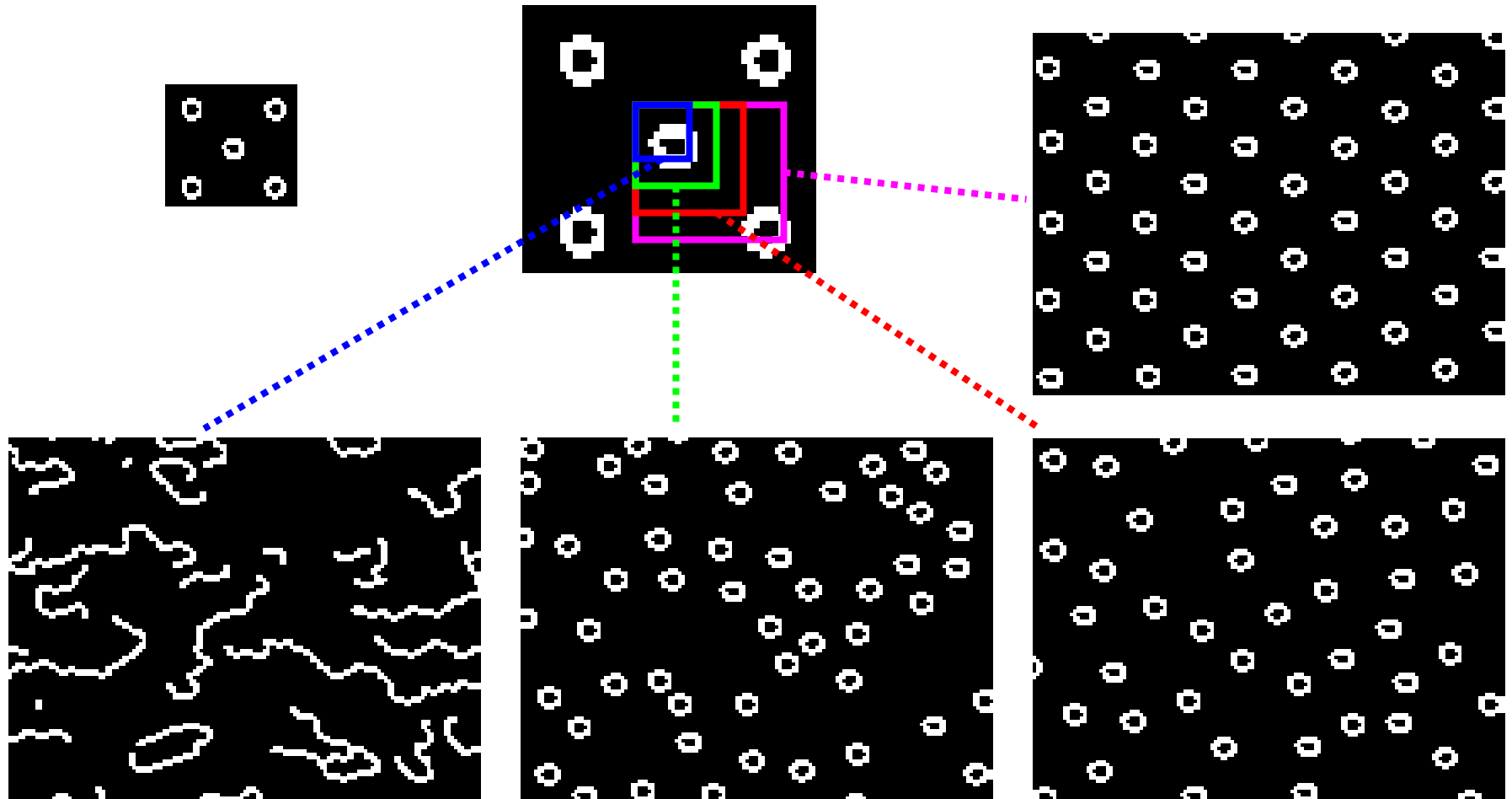
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- Starting from the initial image, “grow” the texture one pixel at a time

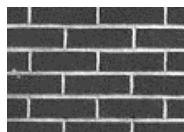
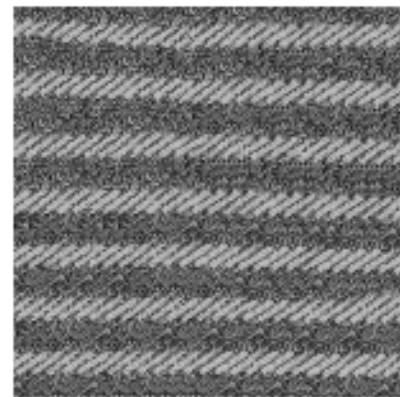
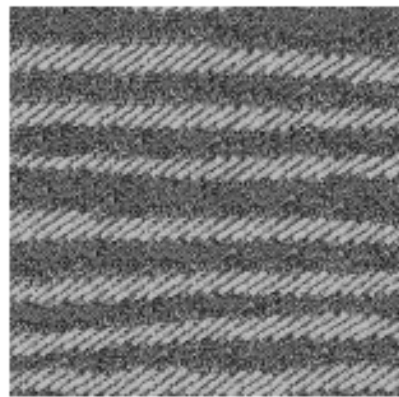
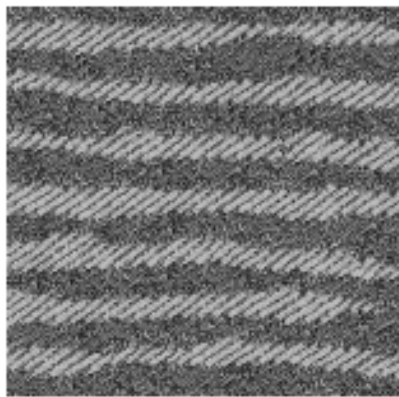
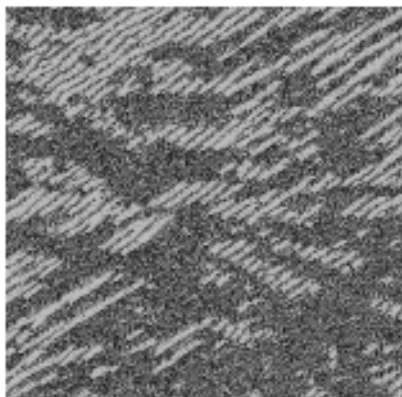
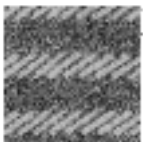
# Window Size Controls Regularity

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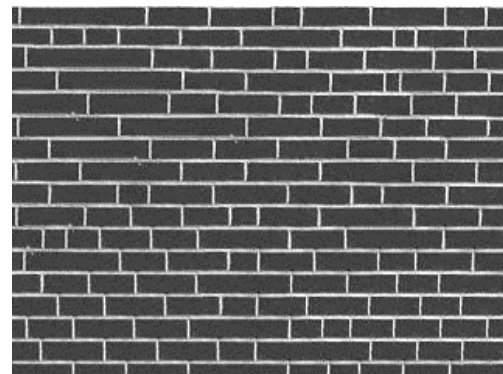
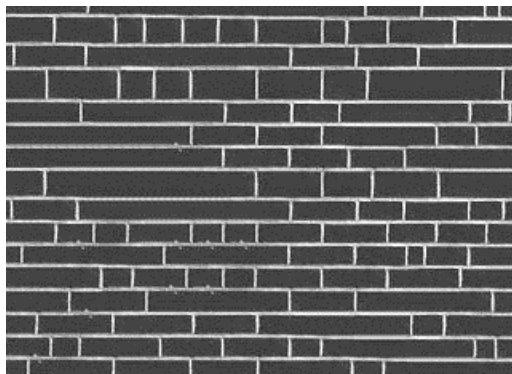
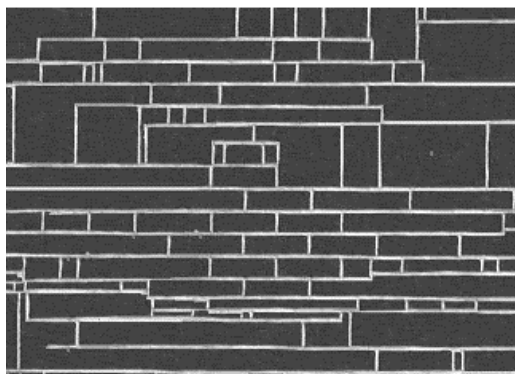


# More Synthesis Results

---



Increasing window size

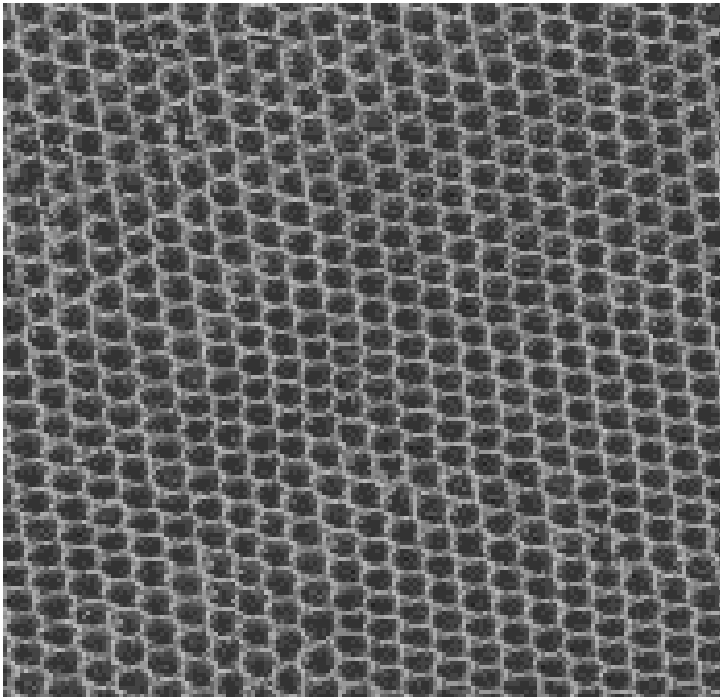
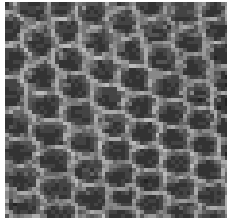




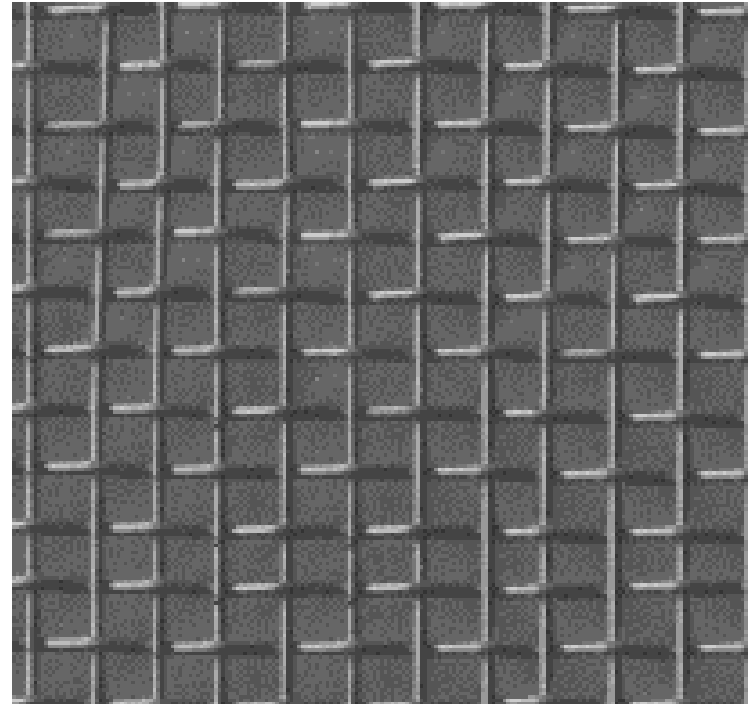
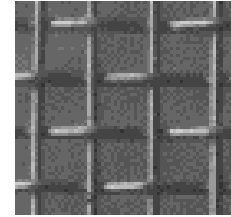
# More Results

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reptile skin

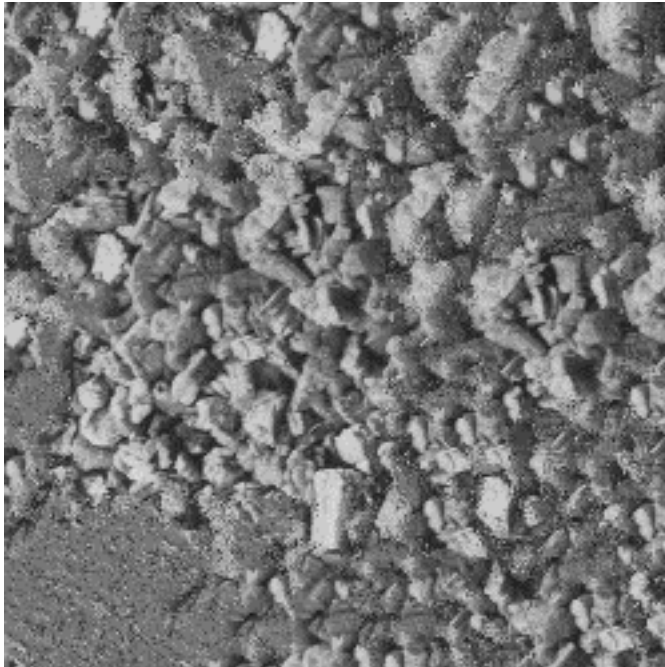
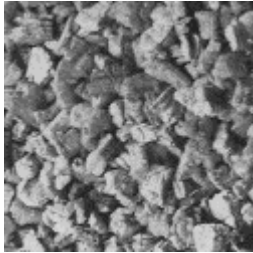


aluminum wire



# Failure Cases

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**Growing garbage**



**Verbatim copying**

# Image-Based Text Synthesis

...it becomes harder to laun-  
d itself, at "this daily  
ving rooms," as House Den  
scribed it last fall. He fail-  
ut he left a ringing question  
ore years of Monica Lewin  
inda Tripp?" That now seen  
Political comedian Al Fran  
ext phase of the story will



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d itself, at "this daily  
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ving rooms," as House Den  
scribed it last fall. He fail-  
ut he left a ringing question  
ore years of Monica Lewin  
inda Tripp?" That now seen  
Political comedian Al Fran  
ext phase of the story will

...ing in the unsensational  
r Dick Gephardt was fail-  
rful riff on the looming  
nly asked, "What's your  
tions?" A heartfelt sigh  
story about the emergen-  
es against Clinton. "Boy  
g people about continuin-  
ardt began, patiently obs-  
s, that the legal system h-  
g with this latest tanger

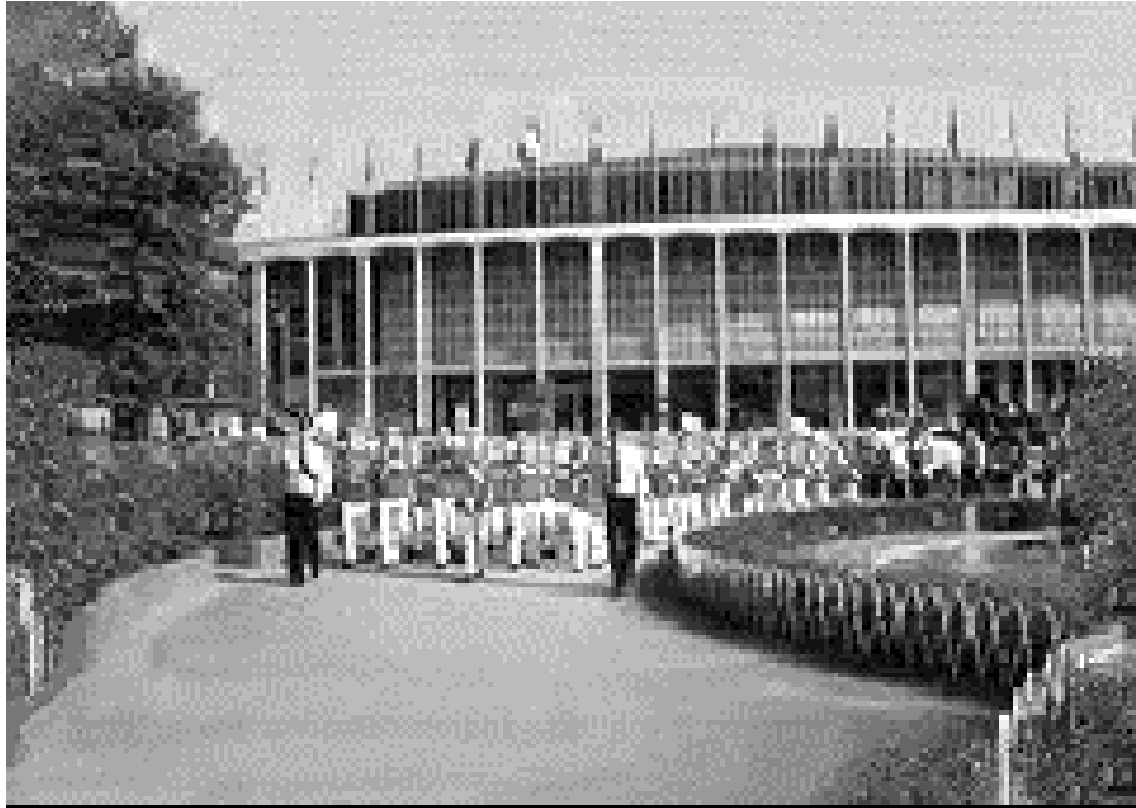


...ing in the unsensational  
r Dick Gephardt was fail-  
rful riff on the looming  
nly asked, "What's your  
tions?" A heartfelt sigh  
story about the emergen-  
es against Clinton. "Boy  
g people about continuin-  
ardt began, patiently obs-  
s, that the legal system h-  
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...ing in the unsensational  
r Dick Gephardt was fail-  
rful riff on the looming  
nly asked, "What's your  
tions?" A heartfelt sigh  
story about the emergen-  
es against Clinton. "Boy  
g people about continuin-  
ardt began, patiently obs-  
s, that the legal system h-  
g with this latest tanger

# Extrapolation

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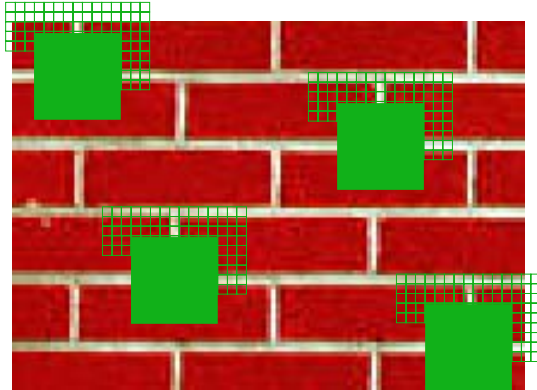
# Speed

---

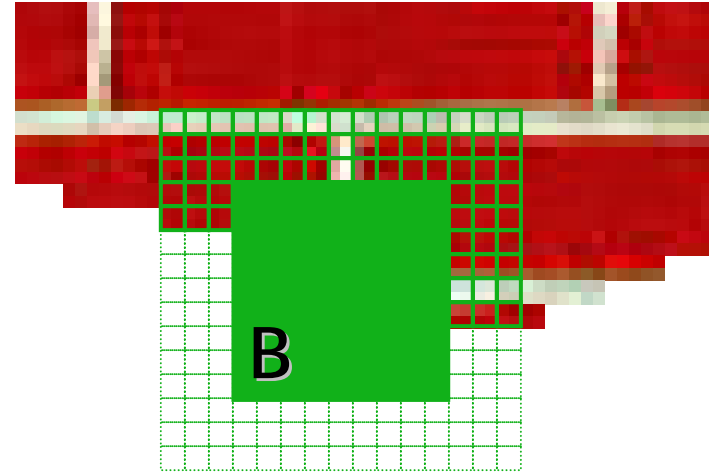
- Given: image of  $k^2$  pixels
- Output: image of  $n^2$  pixels
- how many window comparisons does this algorithm require?

# Block-based texture synthesis

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Input image



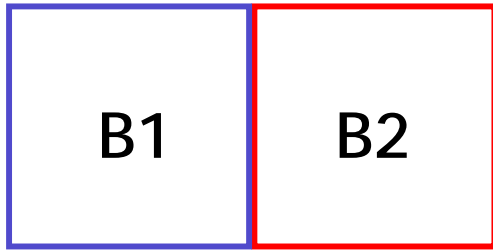
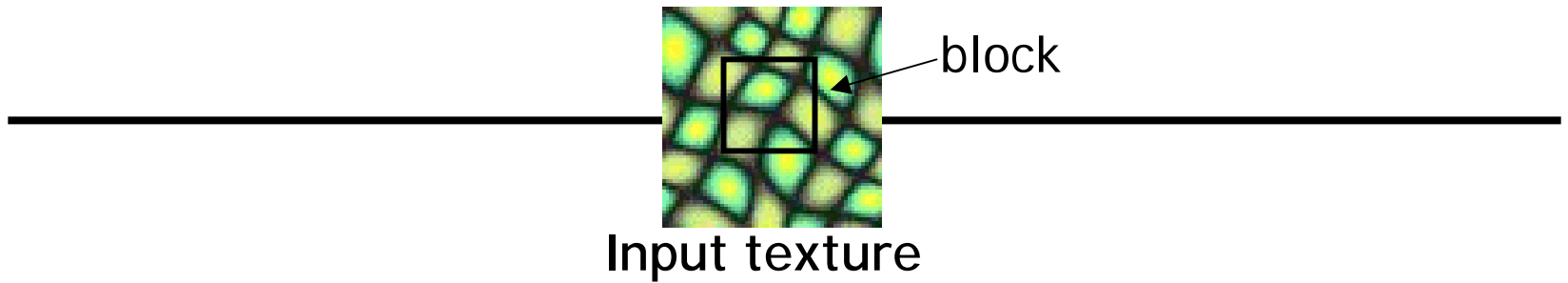
Synthesizing a block

Observation: neighbor pixels are highly correlated

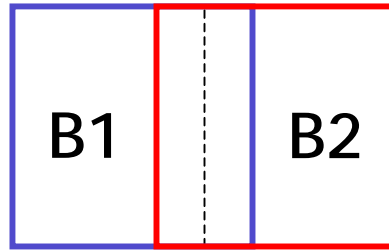
Idea: unit of synthesis = block

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

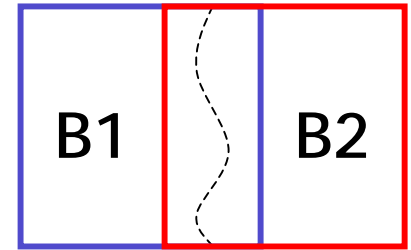
[\*Image Quilting for Texture Synthesis and Transfer\*, Efros & Freeman, SIGGRAPH, 2001.](#)



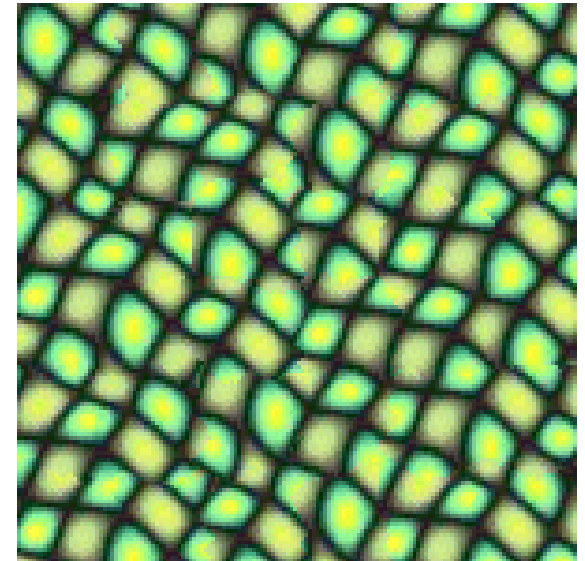
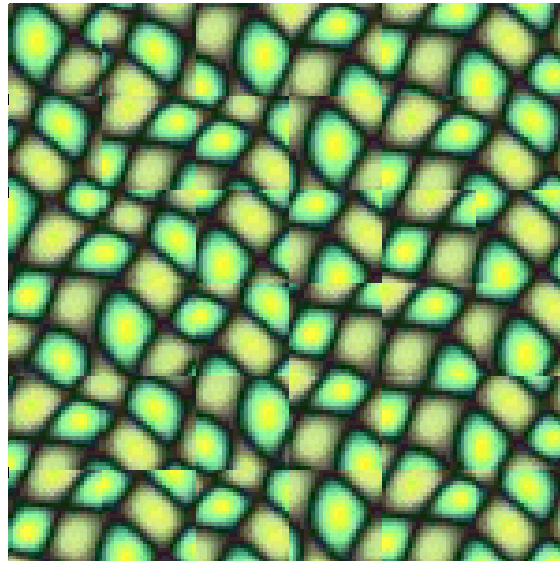
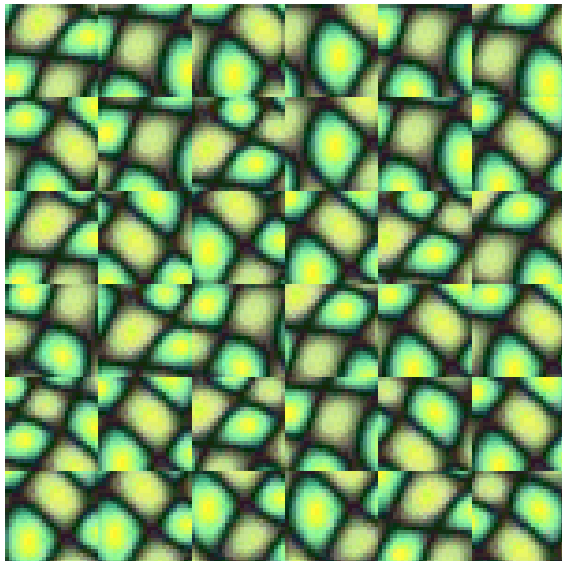
Random placement  
of blocks



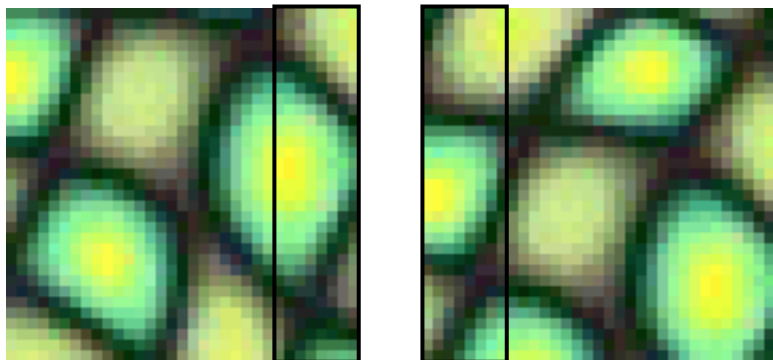
Neighboring blocks  
constrained by overlap



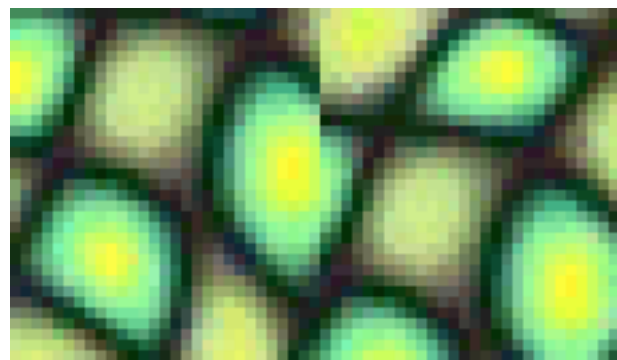
Minimal error  
boundary cut



overlapping blocks

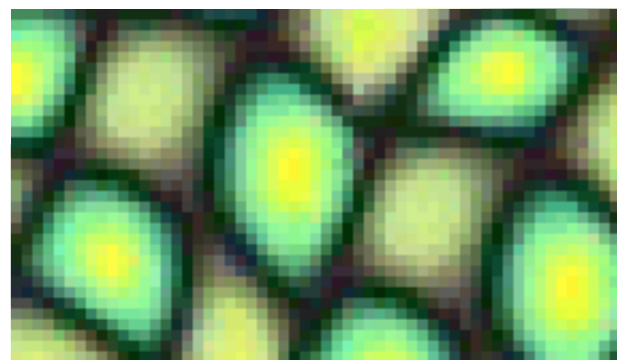


vertical boundary



A diagram illustrating the calculation of overlap error. It shows two vertical strips of the cell image, one on the left and one on the right, with a minus sign between them. These are enclosed in large square brackets. To the right of the brackets is a superscript '2'. This is followed by an equals sign and a vertical strip of the cell image with a red jagged line representing the boundary.

overlap error



min. error boundary



# Fill Order

---



In what order should we fill the pixels?

# Fill Order

---



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]

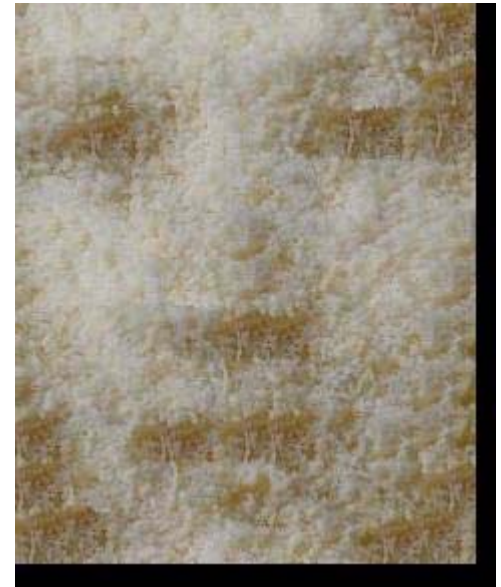
---



Constraint



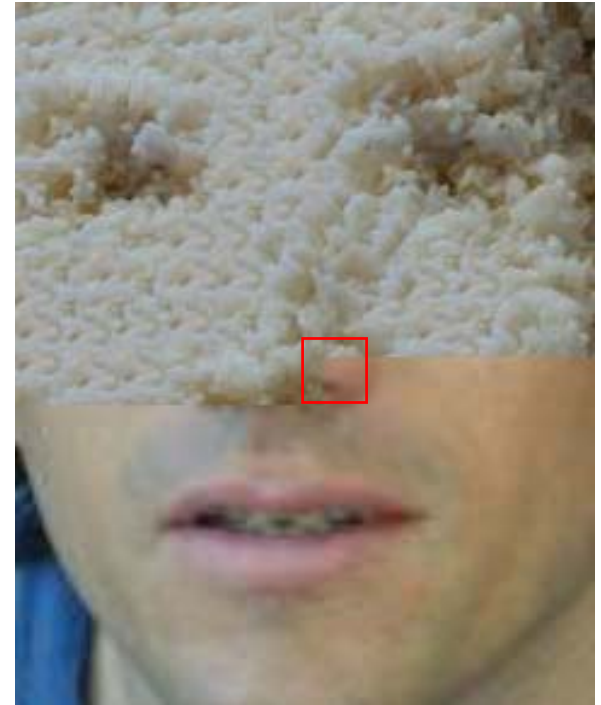
Texture sample



# Texture Transfer

---

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

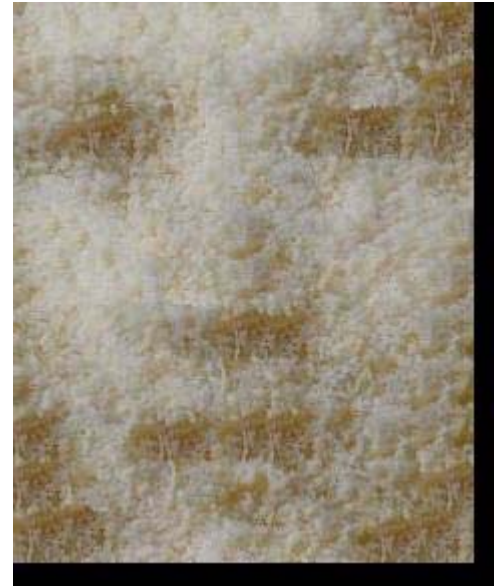




+



=



+

rice



=



# Image repairing (Jia and Tang, '03)

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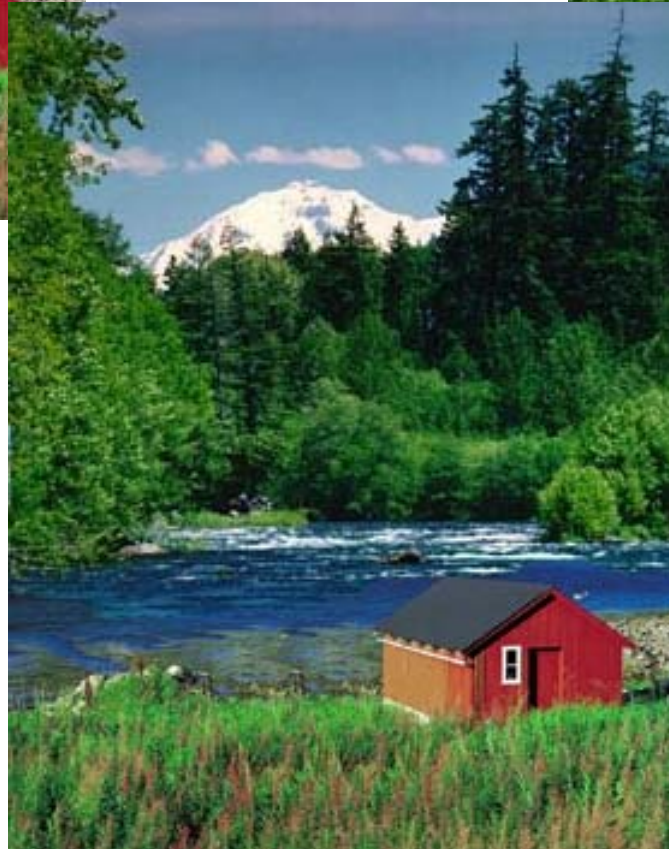


# Combining two images

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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

---



A



A'



B



B'



# Texture-by-numbers

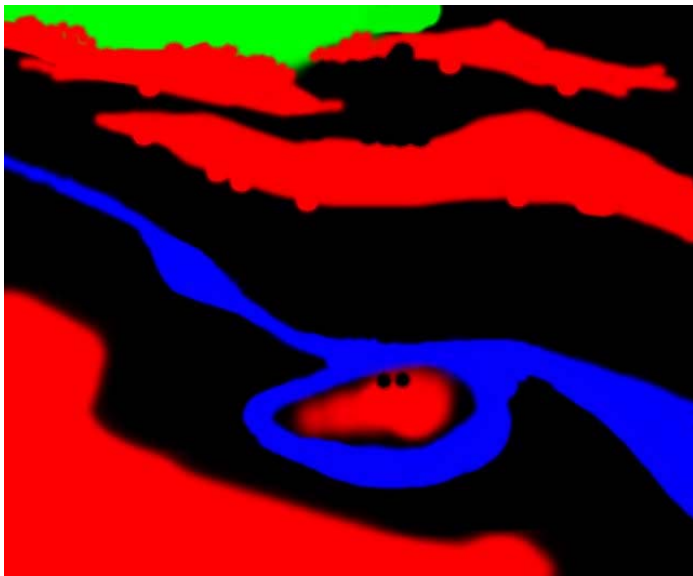
---



A



A'



B



B'

# Colorization

---



A



A'



B



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.