Texture Synthesis

Michael Kazhdan

(601.457/657)

An Image Synthesizer. Perlin, 1985

Texture Synthesis by Non-Parametric Sampling. Efros and Leung, 1999

Image Quilting for Texture Synthesis and Transfer. Efros and Freeman, 2001

Wang Tiles for Image and Texture Generation. Cohen et al., 2003

What is a texture?

Courtesy Paul Bourke

What is a texture?

Texture is an image that exhibits:

- Stationarity – different regions “look similar”

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- Locality – individual pixels related only to small set of neighbors

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What is a texture?

Texture is an image that exhibits:

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e

<u>Note</u>:
Any image can be texture-mapped.
We are focusing on images that are qualitatively *textures*.

How can we get textures?

Photographs

Manual texture synthesis

Automatic texture synthesis

- Procedural generation
- Extrapolation

Photographs

Easy and fast (if we can find the texture we want)!

What if our photo is not big enough?

Courtesy NVIDIA

Photographs

Easy and fast (if we can find the texture we want)!

What if our photo is not big enough?

- Stretching changes scale, image quality

Courtesy NVIDIA

Photographs

Easy and fast (if we can find the texture we want)!

What if our photo is not big enough?

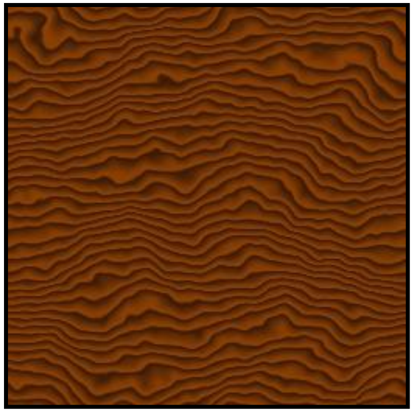
- Stretching changes scale, image quality
- Tiling looks repetitive (and can generate seams)

Manual Texture Synthesis

There are “texture painters”…

- Time consuming
- Difficult

Automatic Texture Synthesis

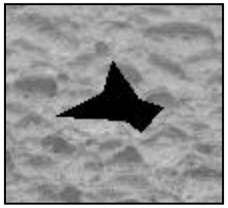


How do we create this

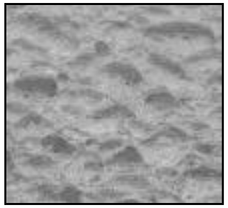
Ex nihilo

How do we go from this…

…to this?



Or from this…



…to this?

Ex materia

Procedural Textures

Generated algorithmically instead of by an artist

Good for certain natural phenomena:

- Wood grain
- Marble
- Fire
- Etc.

Perlin-noise Textures

Key Idea:

Objects in nature (e.g. wood grain, mountain ranges, marble, clouds, fire) are composed of layers of detail

- » Individual layers appear as random signals of a fixed **frequency**
- » The textures are determined by the **amplitudes** at which the different frequencies contribute

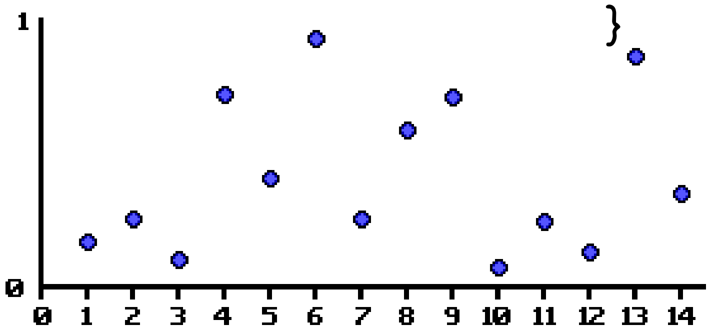
Perlin-noise Textures (Per Layer)

We need:

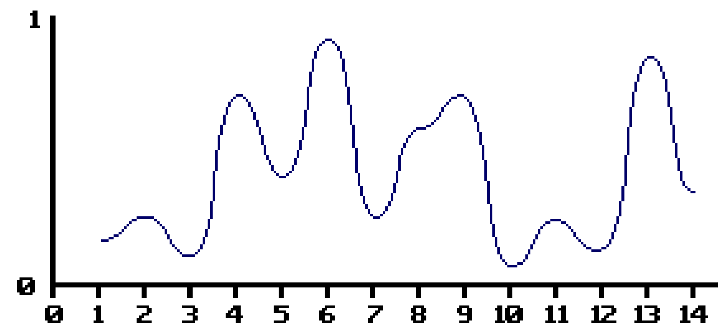
- Noise
- Interpolation

```
void init( float noise[] , int n , float amp )
{
	for( int i=0 ; i<n ; i++ ) noise[i] = Random() * amp;
}

float sample( float x , const float noise[] , int n )
{
	x *= n;
	int ix = (int)floor( x );
	return Interpolate( noise[ix] , noise[ix+1] , x-ix );
}
```



Noise



Interpolation

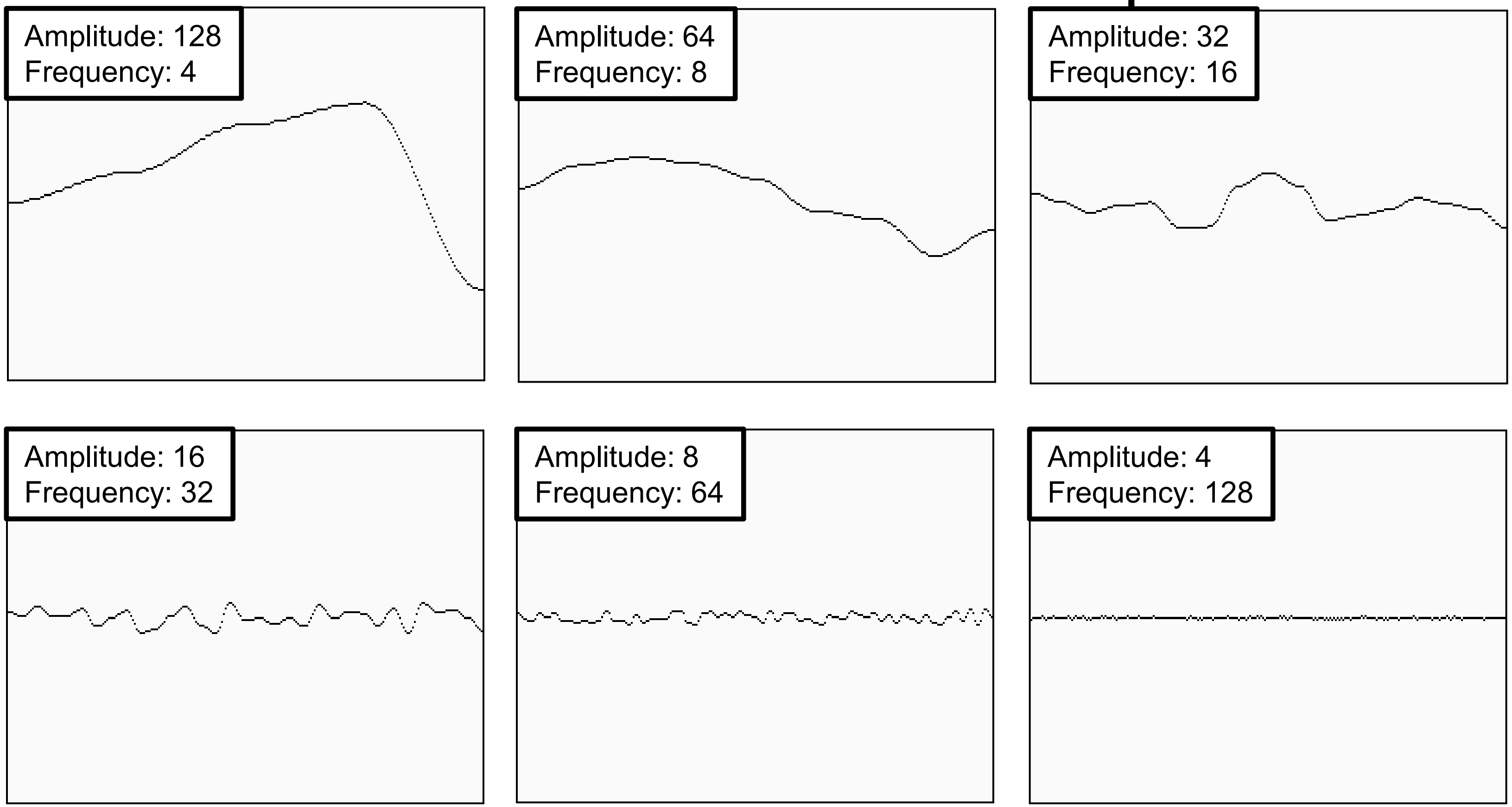
Frequency/Resolution := Number of Samples (n)

Amplitude := Magnitude of the random number

ourtesy Hugo Elias

Perlin-noise Textures

Sum noise at different resolutions/amplitudes

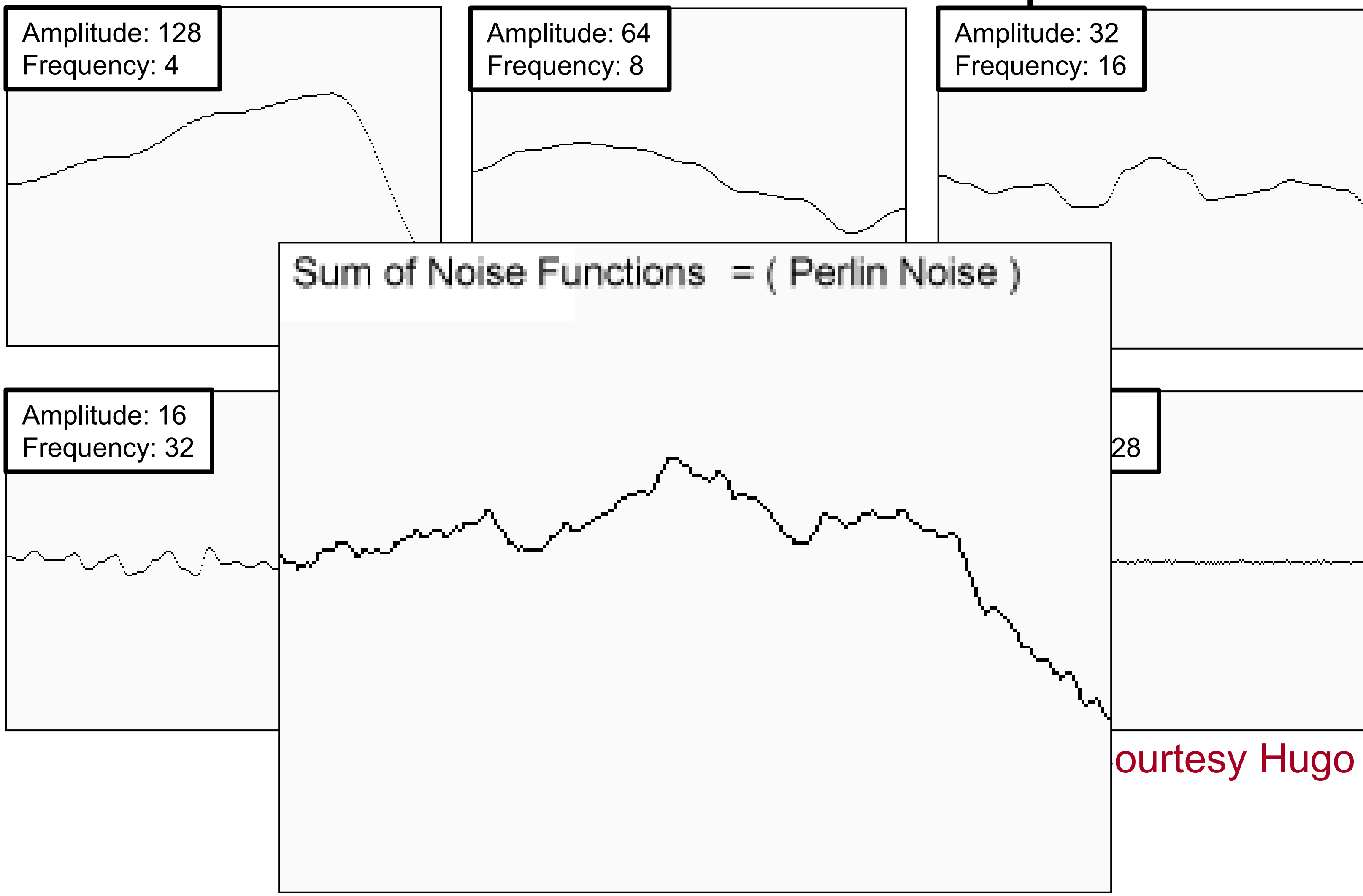


Courtesy Hugo Elias

Standardly:
- Frequencies are powers of two
- Amplitude decreases by a constant factor with frequency.

Perlin-noise Textures

Sum noise at different resolutions/amplitudes



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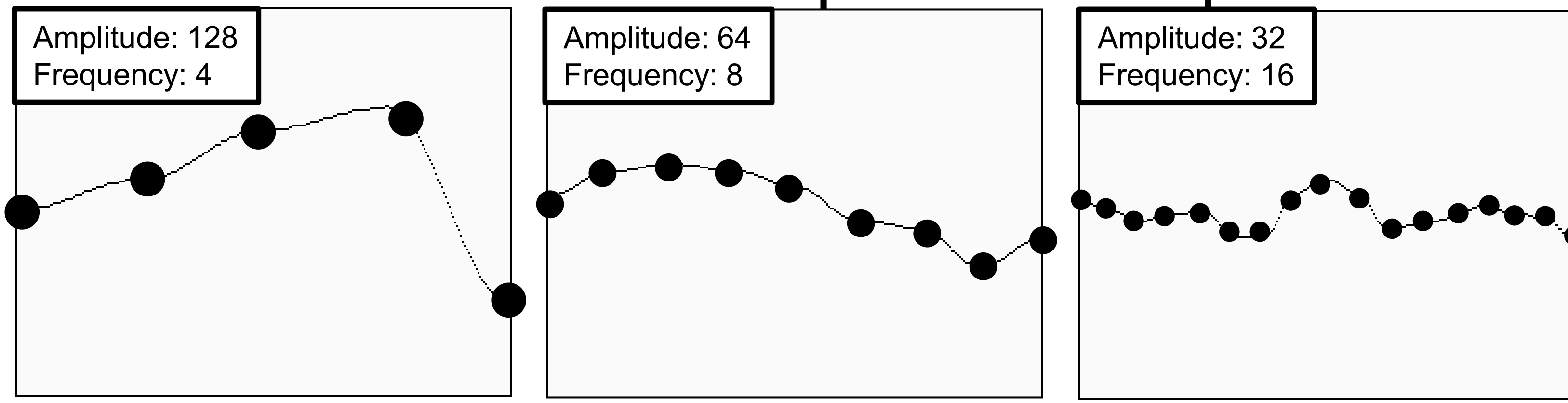
Perlin-noise Textures

Sum noise at different frequencies/amplitudes



How much data would we need to *store* the texture?

If we sample at resolution n, we need $2n$ values:

- n at the finest level
- $n/2$ at the next level,
- etc.

In d dimensions, $O(n^d)$.

```
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    for( int i=0 ; i<n ; i++ ) noise[i] = Random() * amp;
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float sample( float x , const float noise[] )
{
    x *= n;
    int ix = (int)floor( x );
    return Interpolate( noise[ix] , noise[ix+1] , x-ix );
}
```
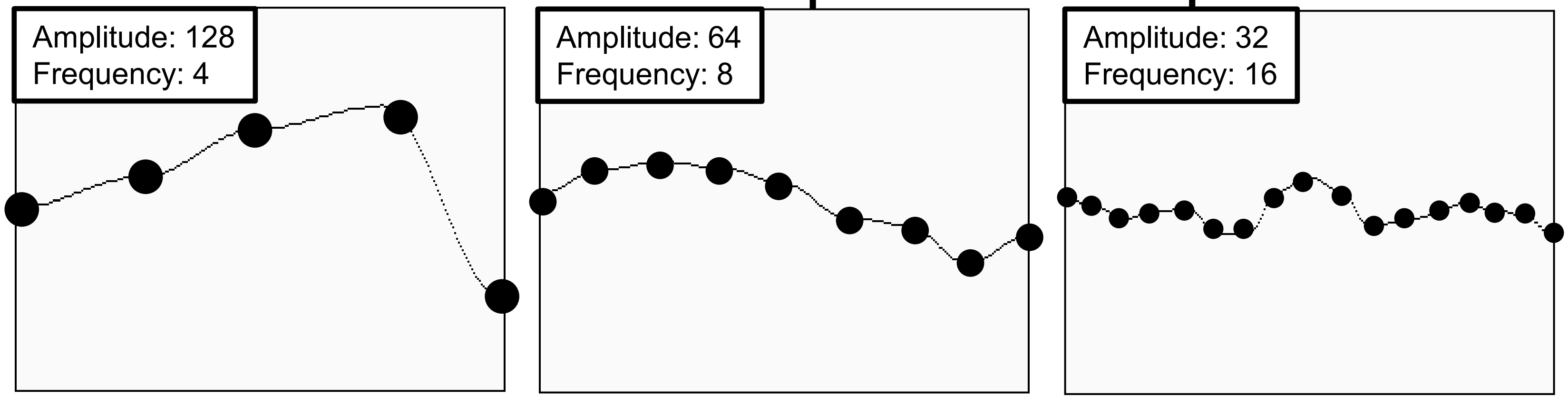

Perlin-noise Textures

Sum noise at different frequencies/amplitudes

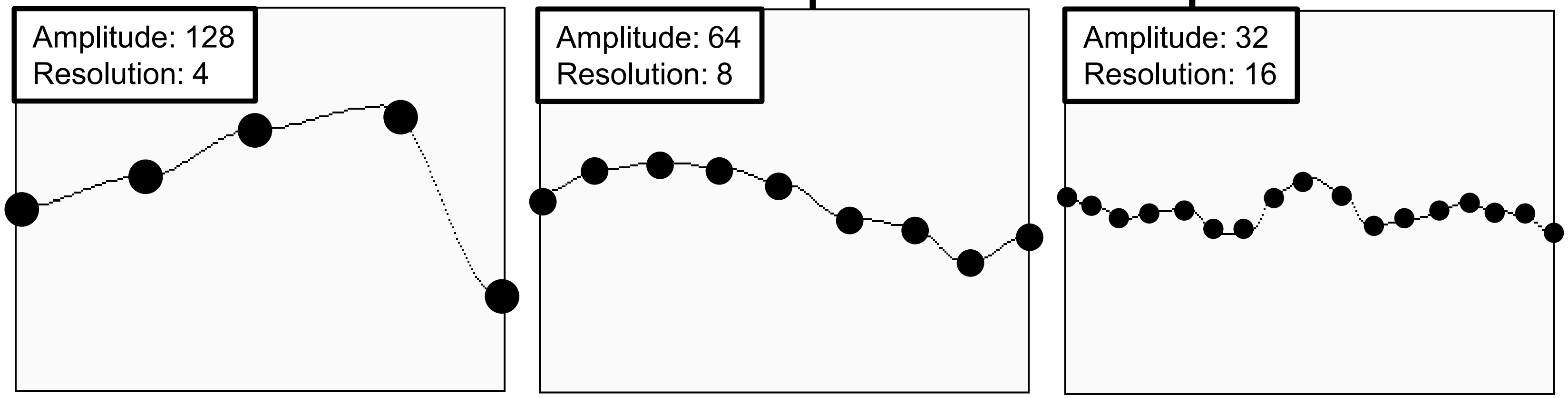


How much data do we need to *sample* the texture?

```
void init( float noise[] , int n , float amp )
{
	for( int i=0 ; i<n ; i++ ) noise[i] = Random() * amp;
}
float sample( float x , const float noise[] )
{
	x *= n;
	int ix = (int)floor( x );
	return Interpolate( noise[ix] , noise[ix+1] , x-ix );
}
```

Perlin-noise Textures

Sum noise at different frequencies/amplitudes



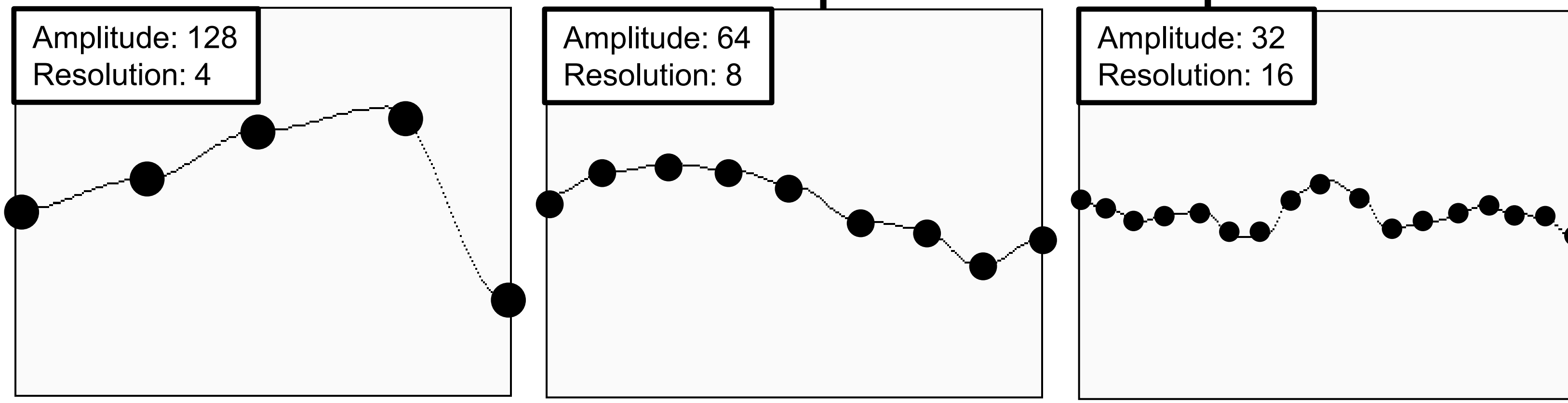
How much data do we need to *sample* the texture?

If we can get the random number generator to always generate the same random value at index *i*, we only need to know the amplitudes.

```
float sample( float x , int n , float amp )
{
        x *= n;
        int ix = (int)floor( x );
        srand( ix );
        float nx0 = Random() * amp;
        srand( ix+1 );
        float nx1 = Random() * amp;
        return Interpolate( nx0 , nx1 , x-ix );
}
```

Perlin-noise Textures

Sum noise at different frequencies/amplitudes



How much *computation* is required to get the value at a point?

Using linear interpolation, we need two values per level. With L levels:

- Generate $2L$ random values
- Interpolate between the L pairs
- Sum the L interpolations

In d dimensions, $O(2^d L)$.

```
float sample( float x , int n , float amp )
{
        x *= n;
        int ix = (int)floor( x );
        srand( ix );
        float nx0 = Random() * amp;
        srand( ix+1 );
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}
```
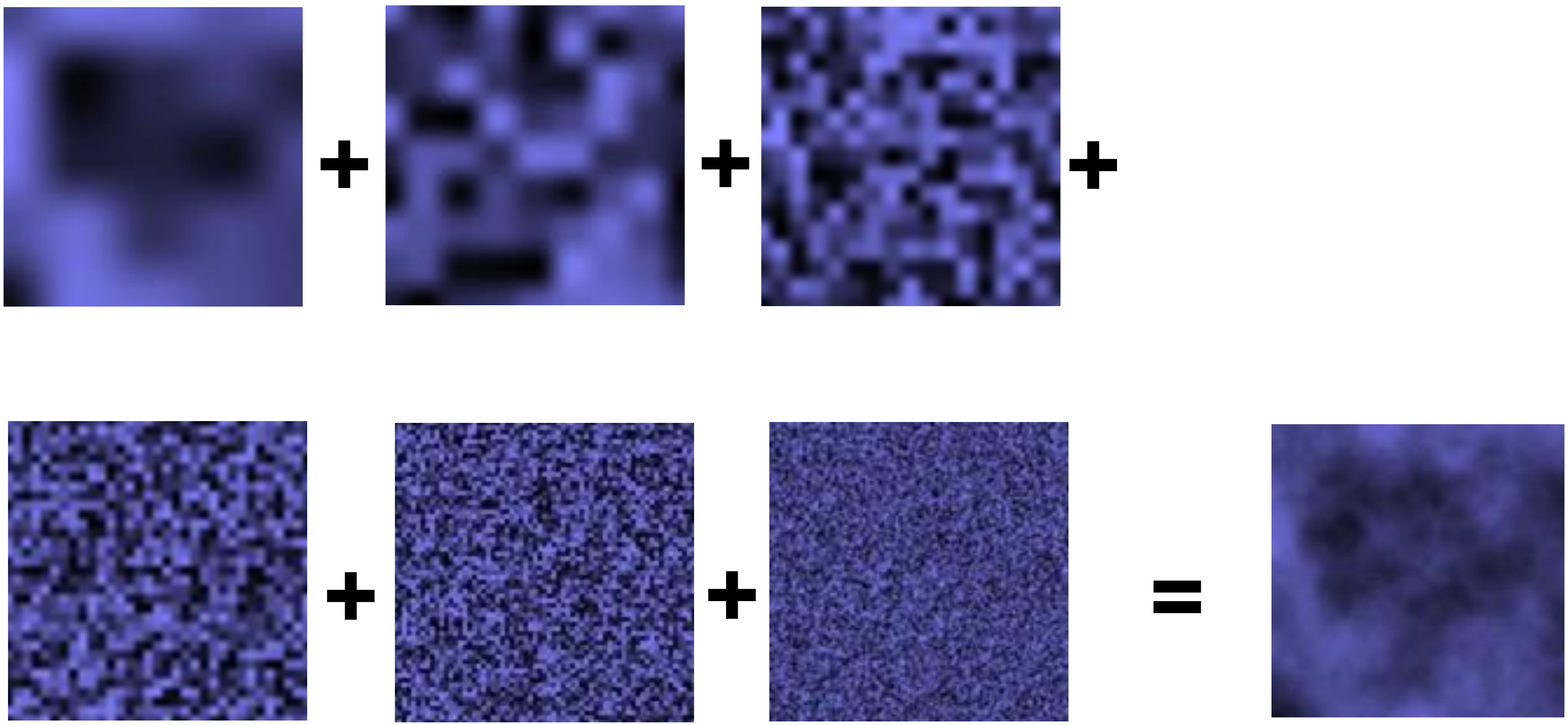

Perlin-noise Textures: Nebula

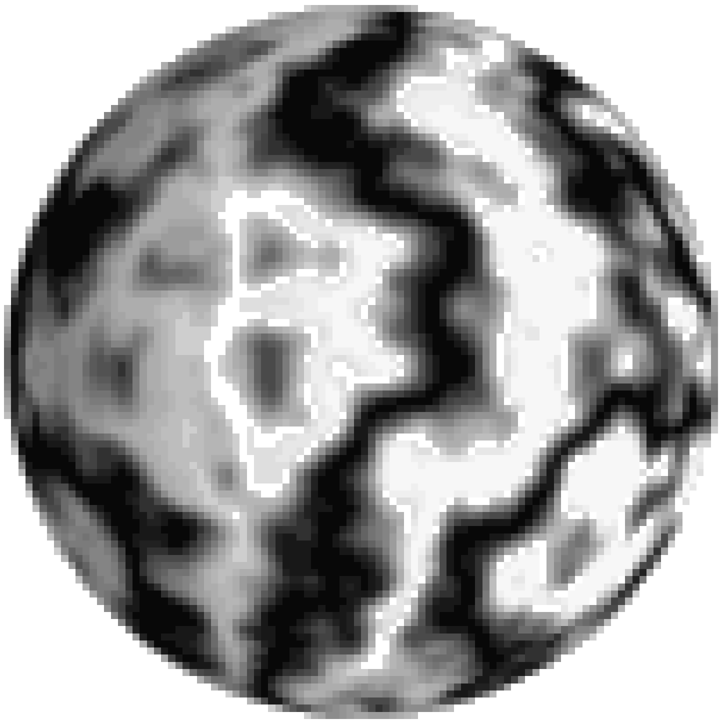
Same idea with 2D images



Courtesy Hugo Elias

Perlin-noise Textures: Marble/Wood

And even 3D textures



Hugo Elias

Note:
We can introduce anisotropy by using different amplitudes for the x-, y-, and z-directions.

Procedural Textures

Pros

- ✓ Constant memory overhead
- ✓ Can be computed efficiently $O(2^d L)$

Cons

- ✗ Only good for certain natural phenomena

Automatic Texture Synthesis

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Ex nihilo

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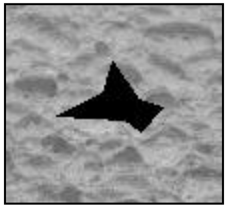

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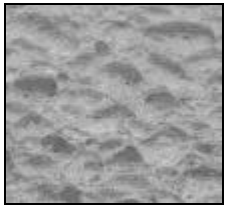


…to this?

Ex materia

Markov Models: Text

Assume we have:

- A fixed alphabet (a through z)
- An input text such as $agggcagcgggcg$

A 0^{th}-order Markov Model:

- Assign probabilities to the characters based on the frequency of their occurrence in the input text:

$$P(a) = \frac{2}{13} \quad P(c) = \frac{3}{13} \quad P(g) = \frac{8}{13}$$

- Assuming characters are <u>independent</u>, generate new text by "coin-flipping".

Markov Models: Text

But each character *is not* independent of previous characters!

A k^{th}-order Markov Model:

- Assigns probabilities to a character's occurrence that depends on the previous k characters.

Markov Models: Text

Assume we have input text with:

- 100 occurrences of th
  - 50 of which followed by e (the, $then$, etc.)
  - 25 of which followed by i ($this$, $thin$, etc.)
  - 20 of which followed by a ($that$, $thank$, etc.)
  - 5 of which followed by o ($though$, $thorn$, etc.)

2nd-order Markov model predicts that:

$$P(e|th) = \frac{1}{2} \quad P(i|th) = \frac{1}{4} \quad P(a|th) = \frac{1}{5} \quad P(o|th) = \frac{1}{20}$$

Given this probabilistic model and a seed, we can generate new text!

Markov Models: Text

Snippet of original text: “As You like it” by Shakespeare:

DUKE SENIOR:

Now, my co-mates and brothers in exile,
Hath not old custom made this life more sweet
Than that of painted pomp? Are not these woods
More free from peril than the envious court?
Here feel we but the penalty of Adam,
The seasons' difference, as the icy fang
And churlish chiding of the winter's wind,
Which, when it bites and blows upon my body,
Even till I shrink with cold, I smile and say
'This is no flattery: these are counsellors
That feelingly persuade me what I am.’ ….

Markov Models: Text

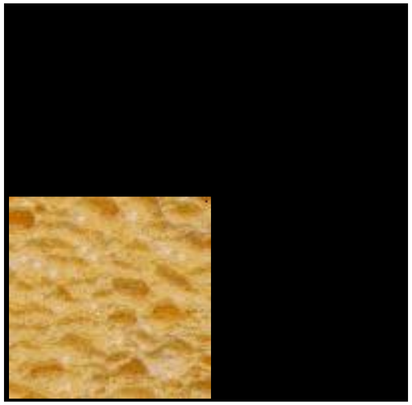
Snippet of generated text with 6th-order Markov Model:

DUKE SENIOR:

Now, my co-mates and thus bolden'd, man, how now, monsieur Jaques, Unclaim'd of his absence, as the holly! Though in the slightest for the fashion of his absence, as the only wear.

Markov Models: Images

Use this as original "text"



and this as seed

to get this result!

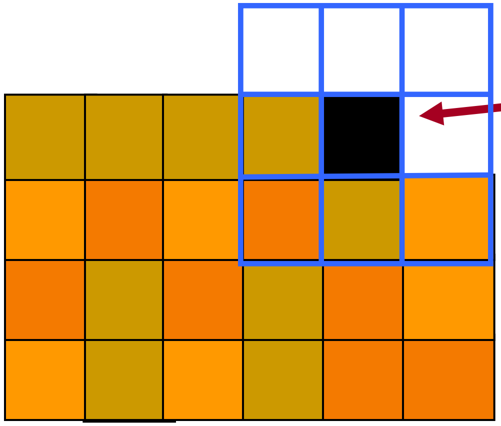
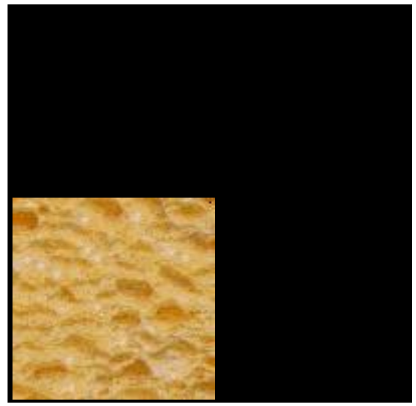


Figure out values of new pixels based on surrounding known pixels

Markov Models: Images

Use this as original "text"



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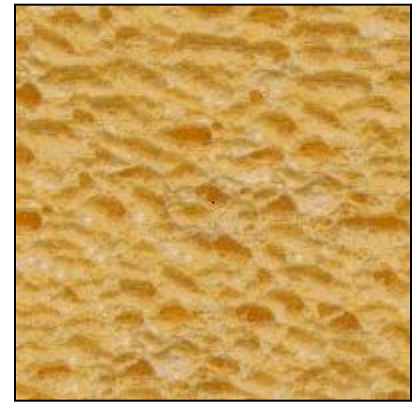

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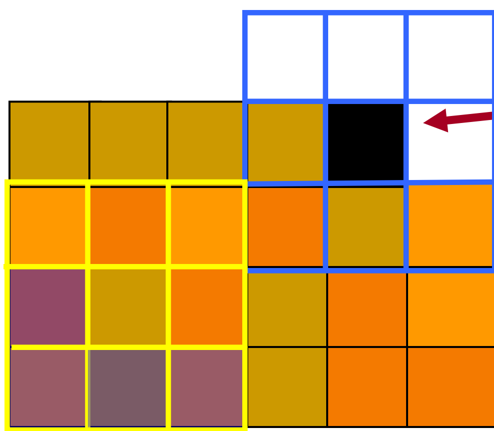

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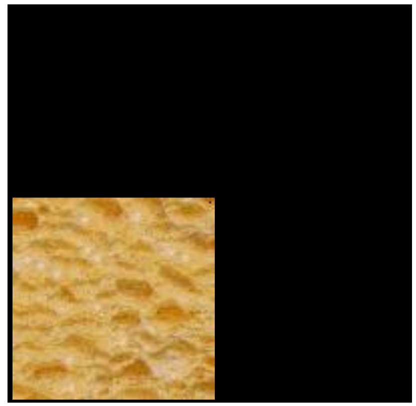

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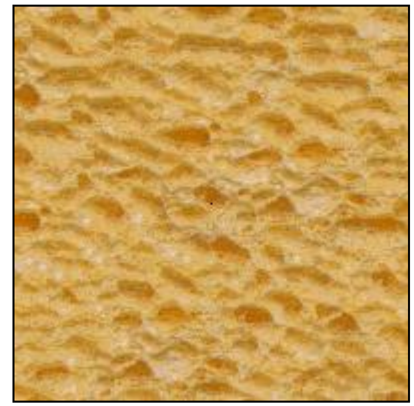

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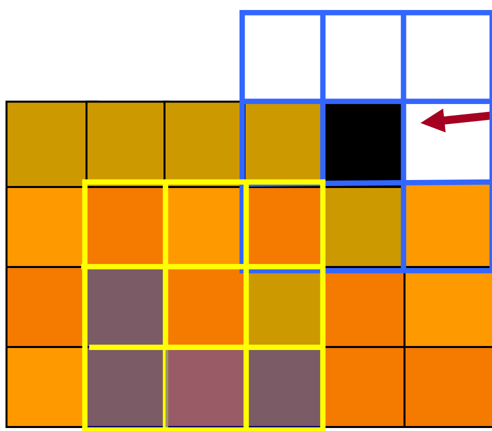

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Markov Models: Images

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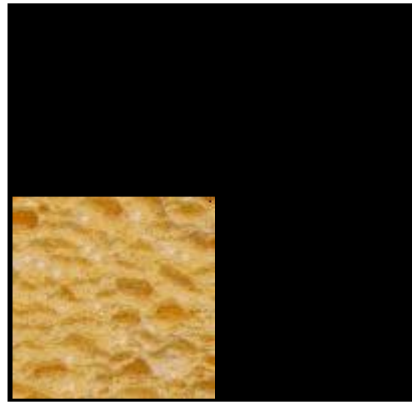

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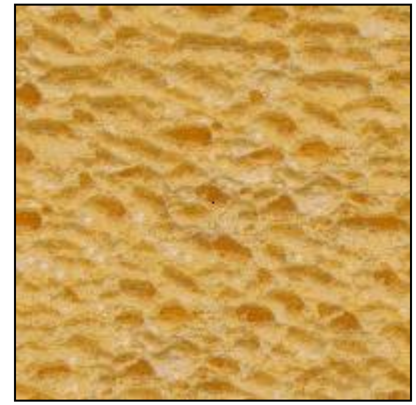

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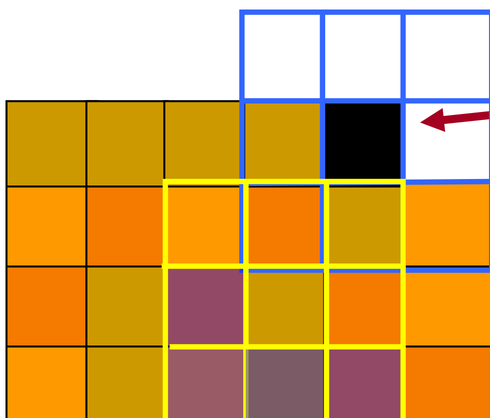


Figure out values of new pixels based on surrounding known pixels

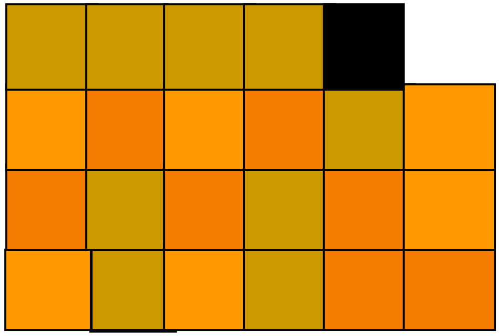
Markov Models: Images

<u>Problems</u>:

- For a given neighborhood, might be only 1 match
  ⇒ Resulting texture too obviously similar to the input
- For a given neighborhood, there may be no matches

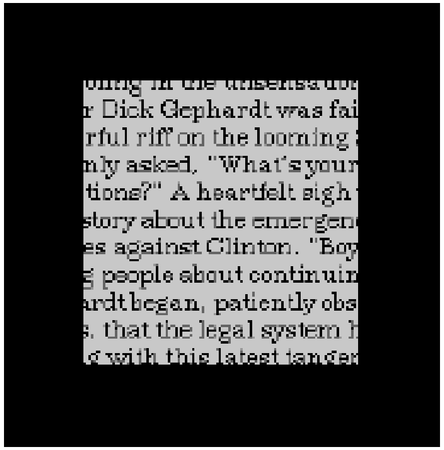
<u>Solution</u>:

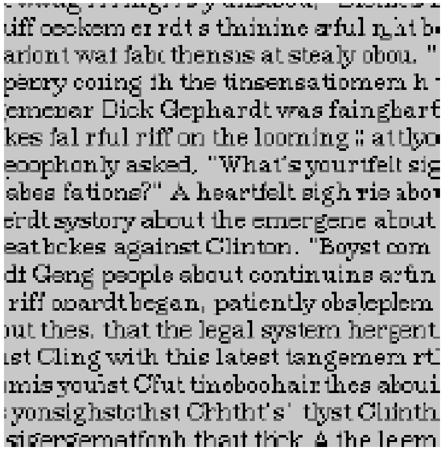
- Randomly choose among best N matches with probability based on match quality



Markov Models: Images

Examples:





Markov Models: Images

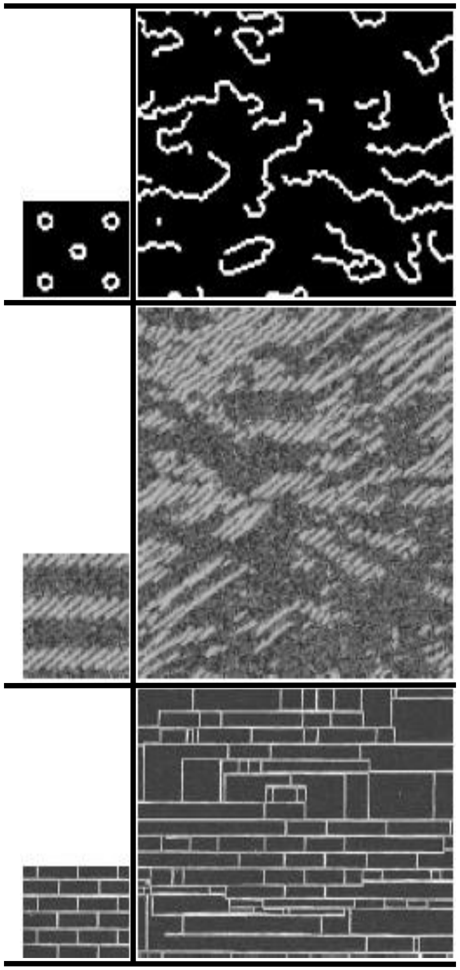
Pros:

- ✓ Conceptually simple/sound
- ✓ Often produces good results
- ✓ Never chooses a pixel/color NOT found in source

Cons:

- ✗ Need to choose correct window size

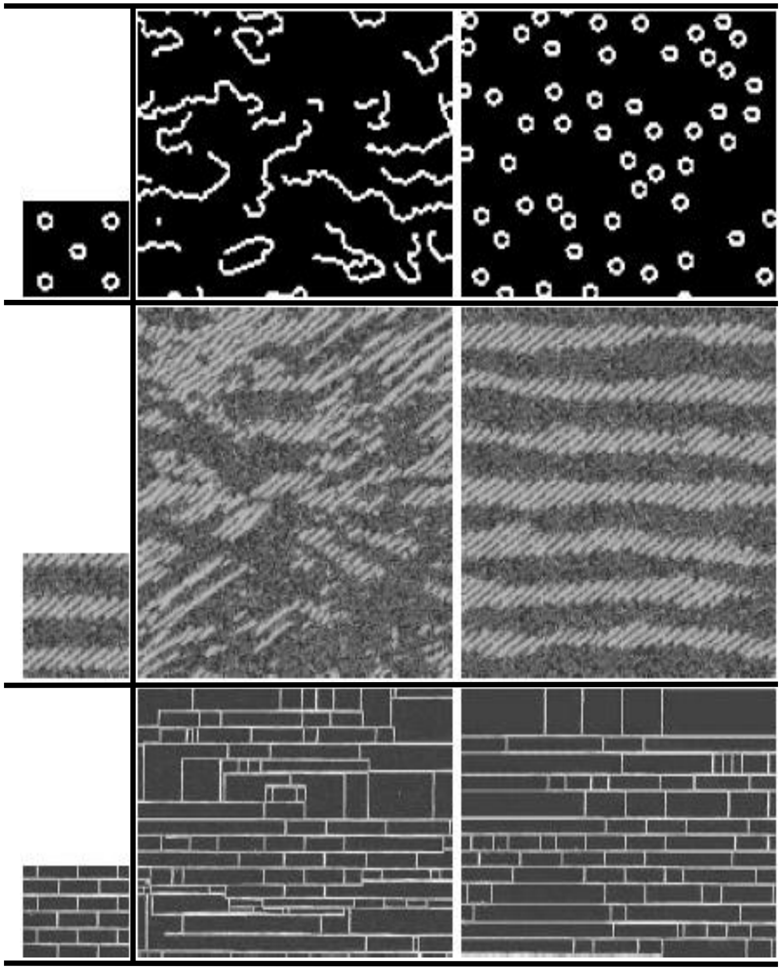
Markov Models: Images



Increasing window size

Courtesy Alexei Efros

Markov Models: Images



Increasing window size →

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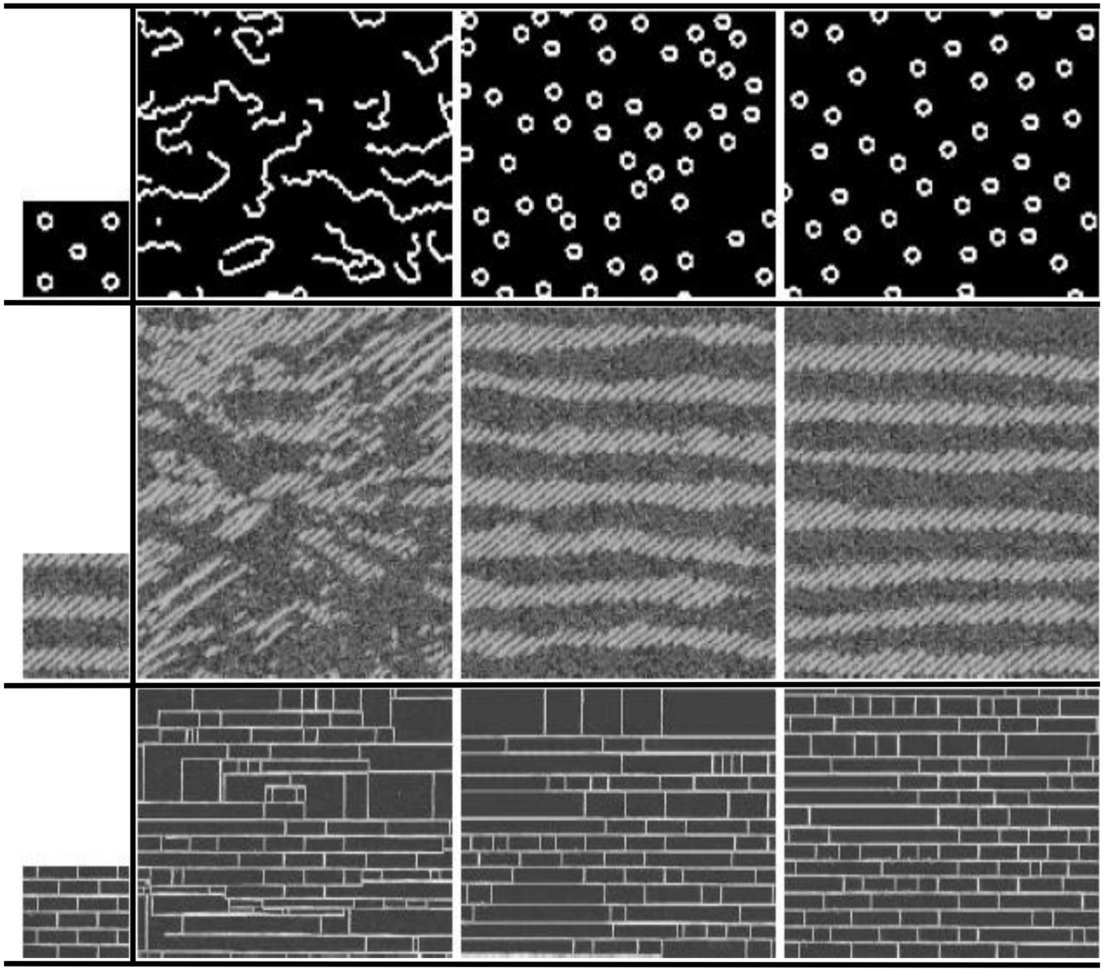
Markov Models: Images



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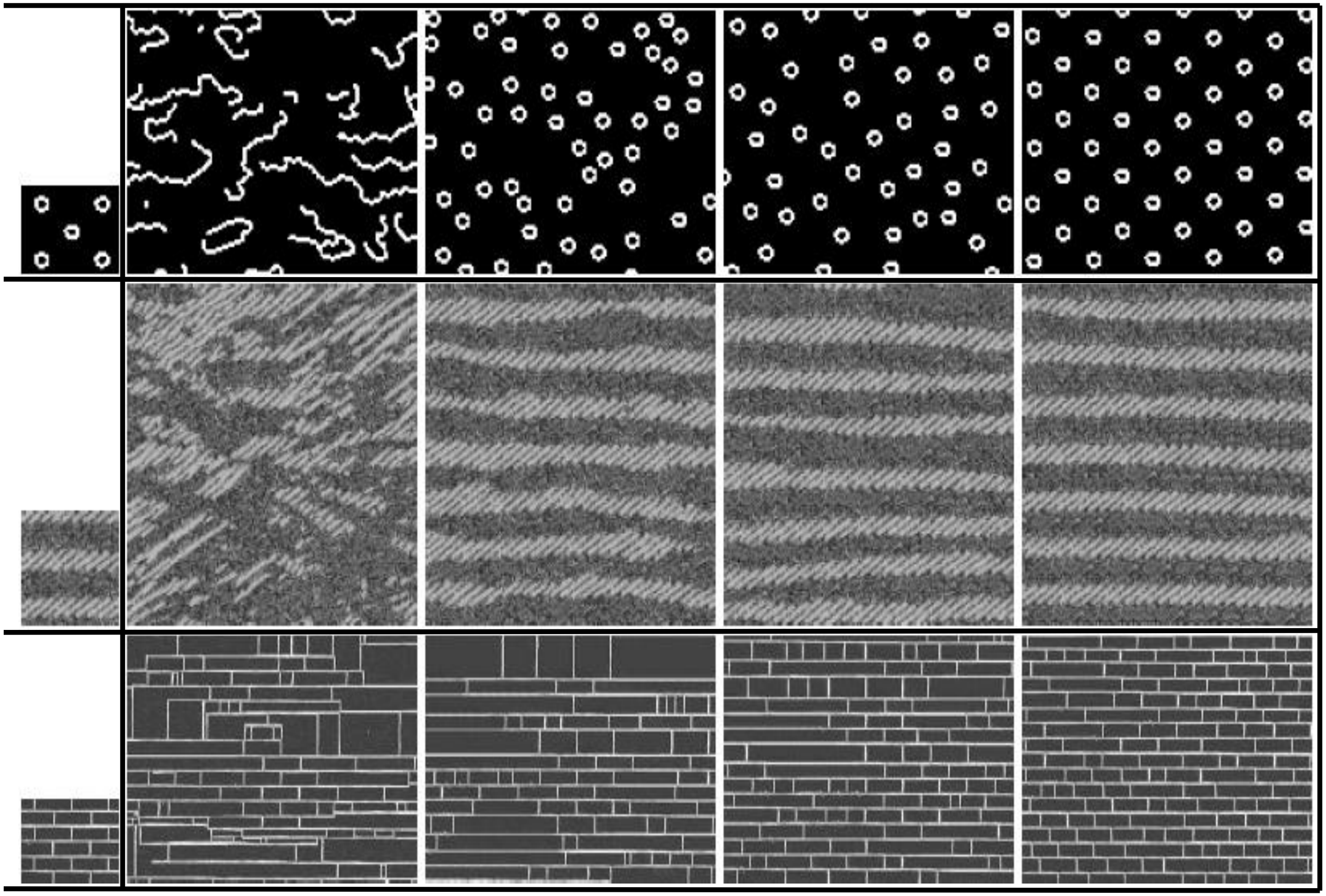
Markov Models: Images



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Pros:

- ✓ Conceptually simple/sound
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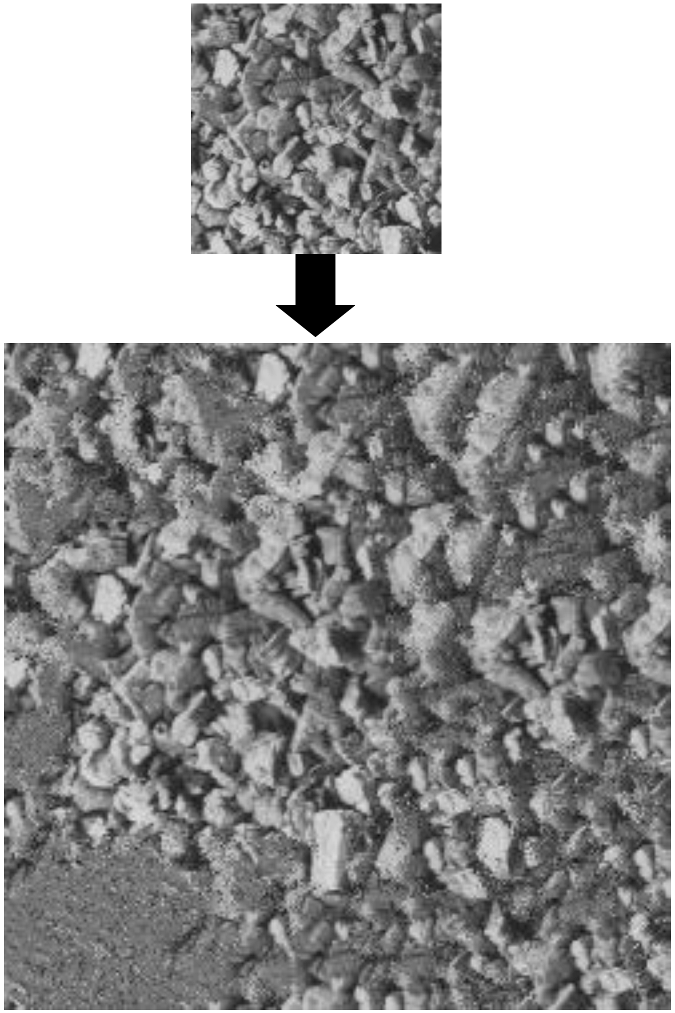
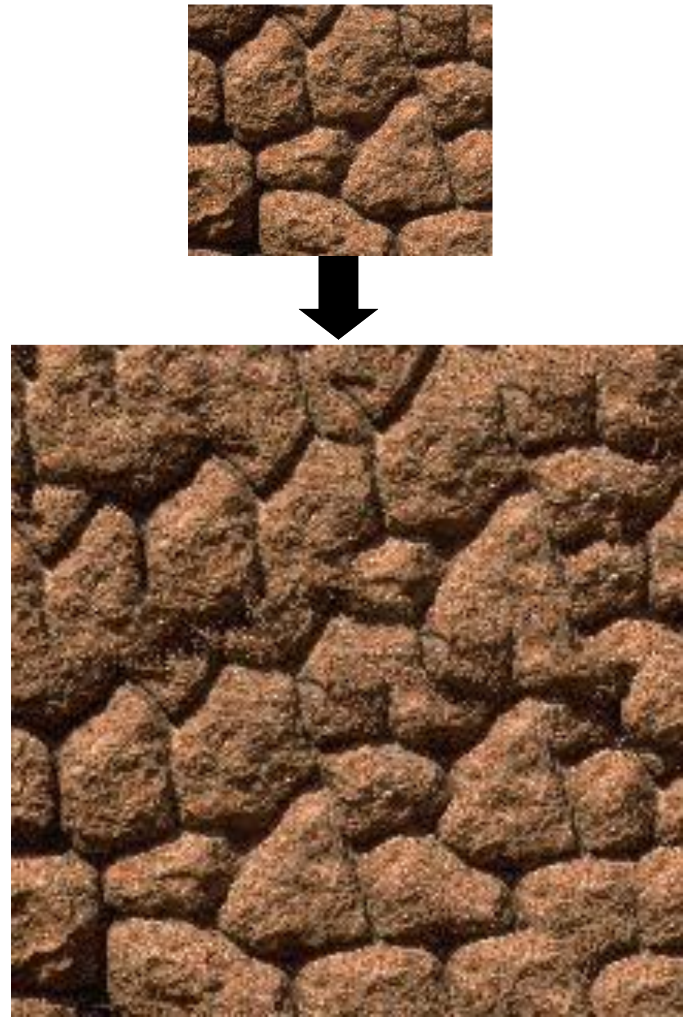
Cons:

- ✗ Need to choose correct window size
- ✗ Slow! (increasing window size makes this worse)
  - » See [Barnes, ‘09] for acceleration techniques

Markov Models: Images



Growing garbage



Verbatim copying

Courtesy Alexei Efros

Markov Models: Images

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- ✓ Never chooses a pixel/color NOT found in source

Cons:

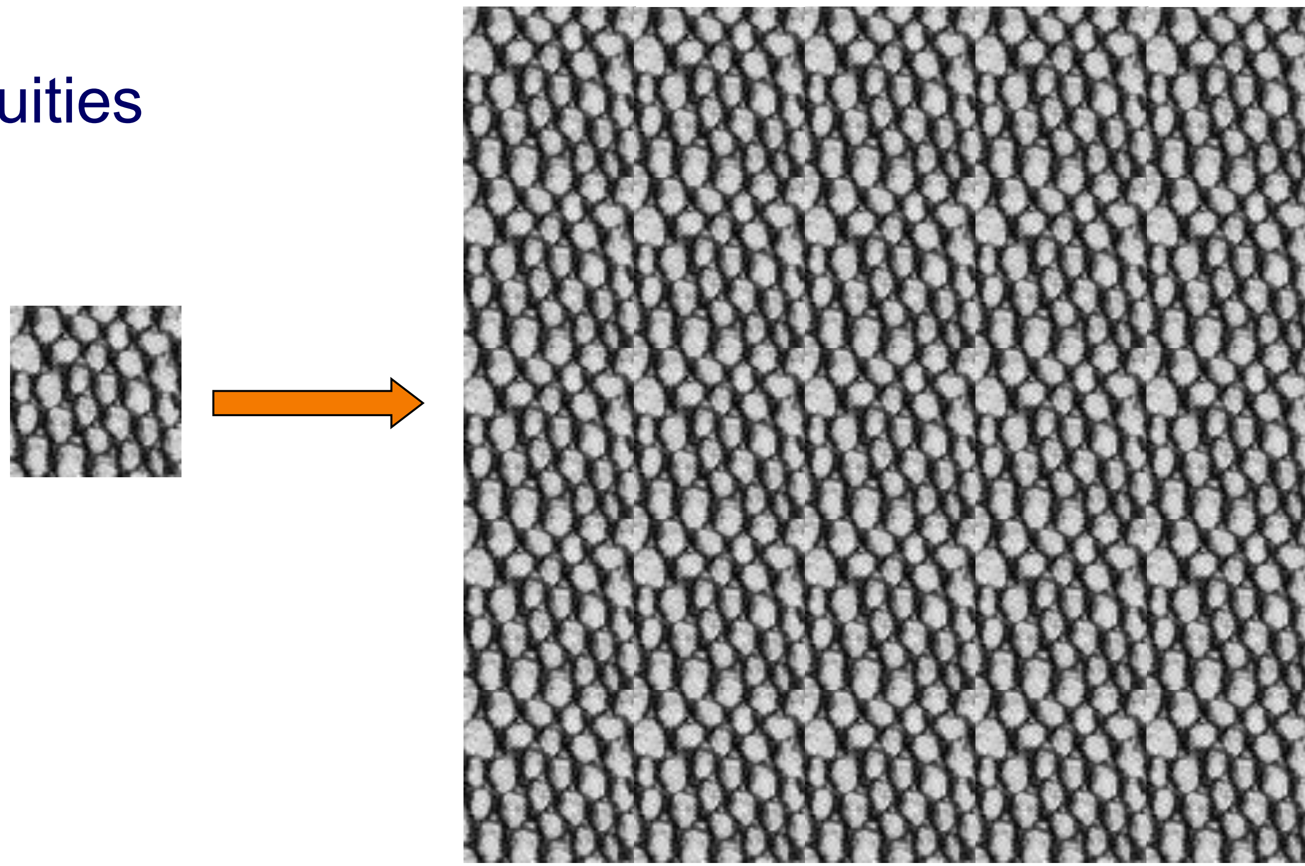
- ✗ Need to choose correct window size
- ✗ Very slow! (increasing window size makes this worse)
- ✗ Doesn't always work (can get stuck in a rut)
- ✗ **The size of the output texture is proportional to the size of the output texture**

Wang Tiles

Can we use a small amount of texture memory to generate large textures?

Tiling:

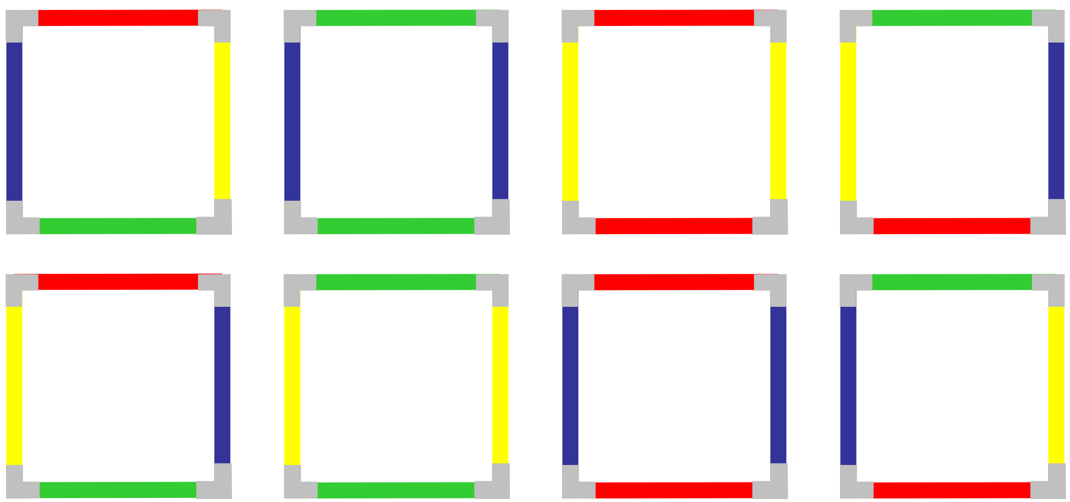
- discontinuities
- repetitive



Wang Tiles

Key Idea:

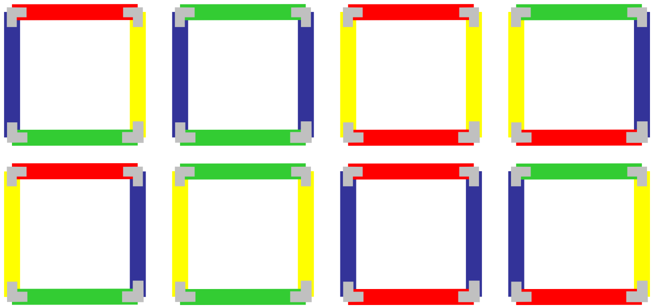
Given a set of colors, and given a sufficiently large set of square tiles whose edges are marked with one of these colors:



Wang Tiles

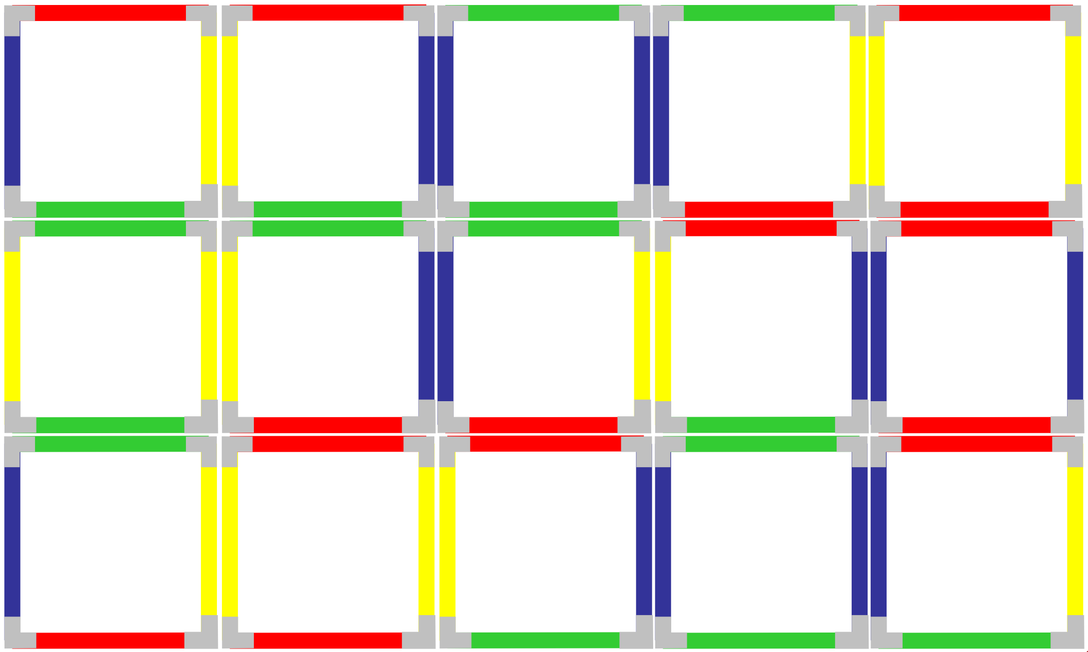
Key Idea:

The plane can be tiled with edge-matching squares:



Base Tiles

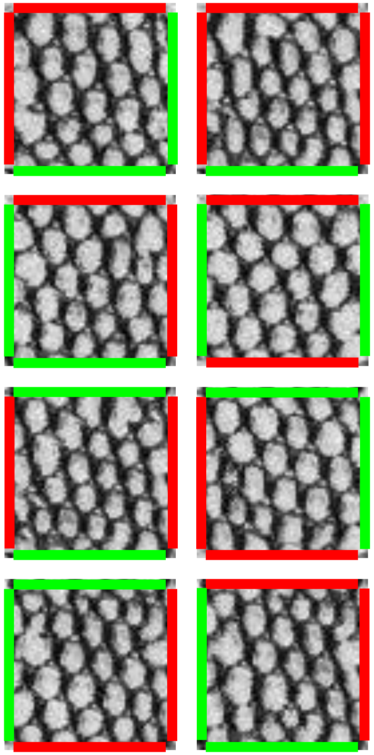
Tiled Image



How Wang Tile Works

Application:

- Associate a single texture to each tile



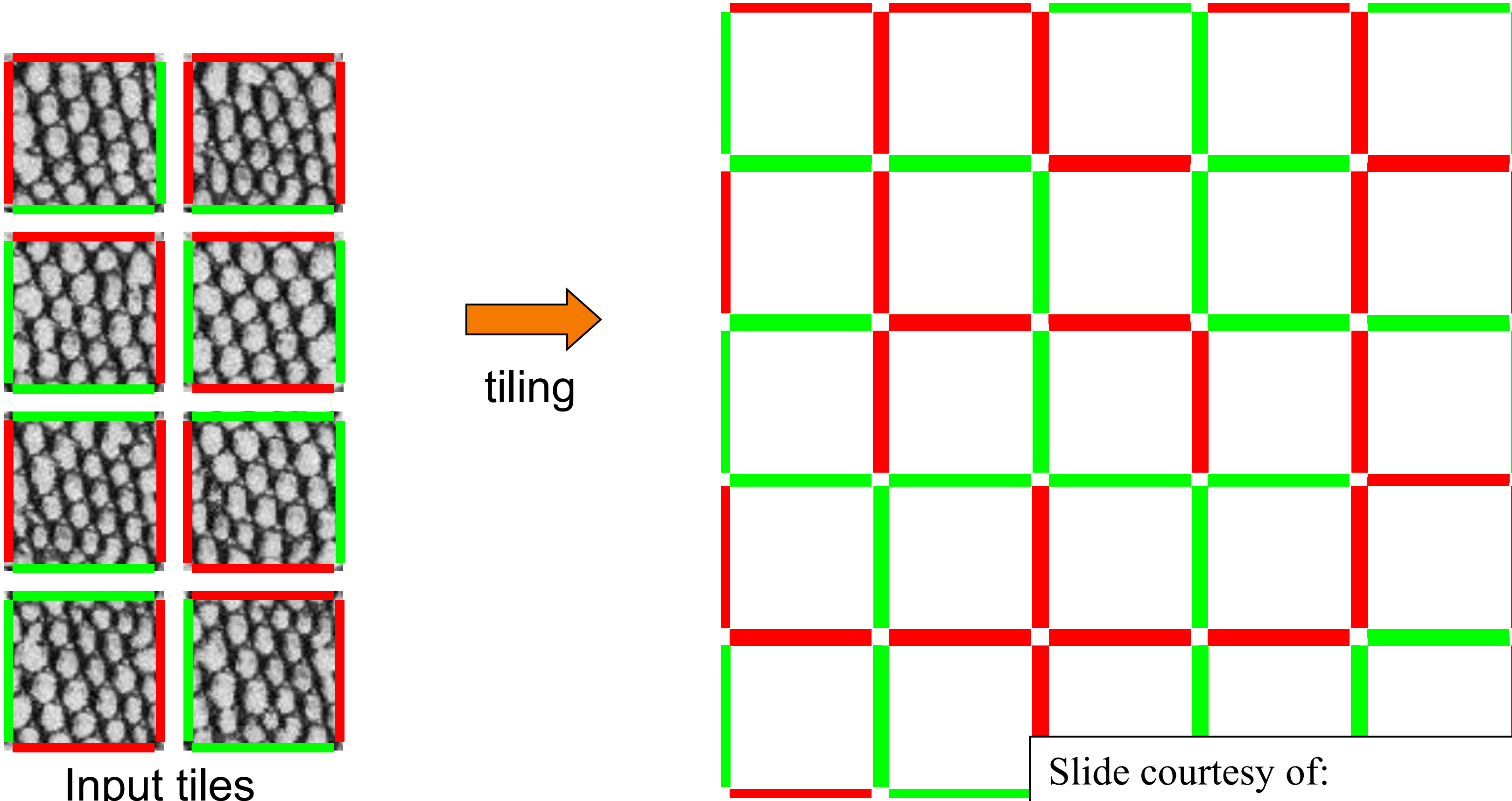
Input tiles

Slide courtesy of:
http://www.graphicshardware.org

How Wang Tile Works

Application:

- Associate a single texture to each tile
- Given a Wang tiling of the plane we get a new texture



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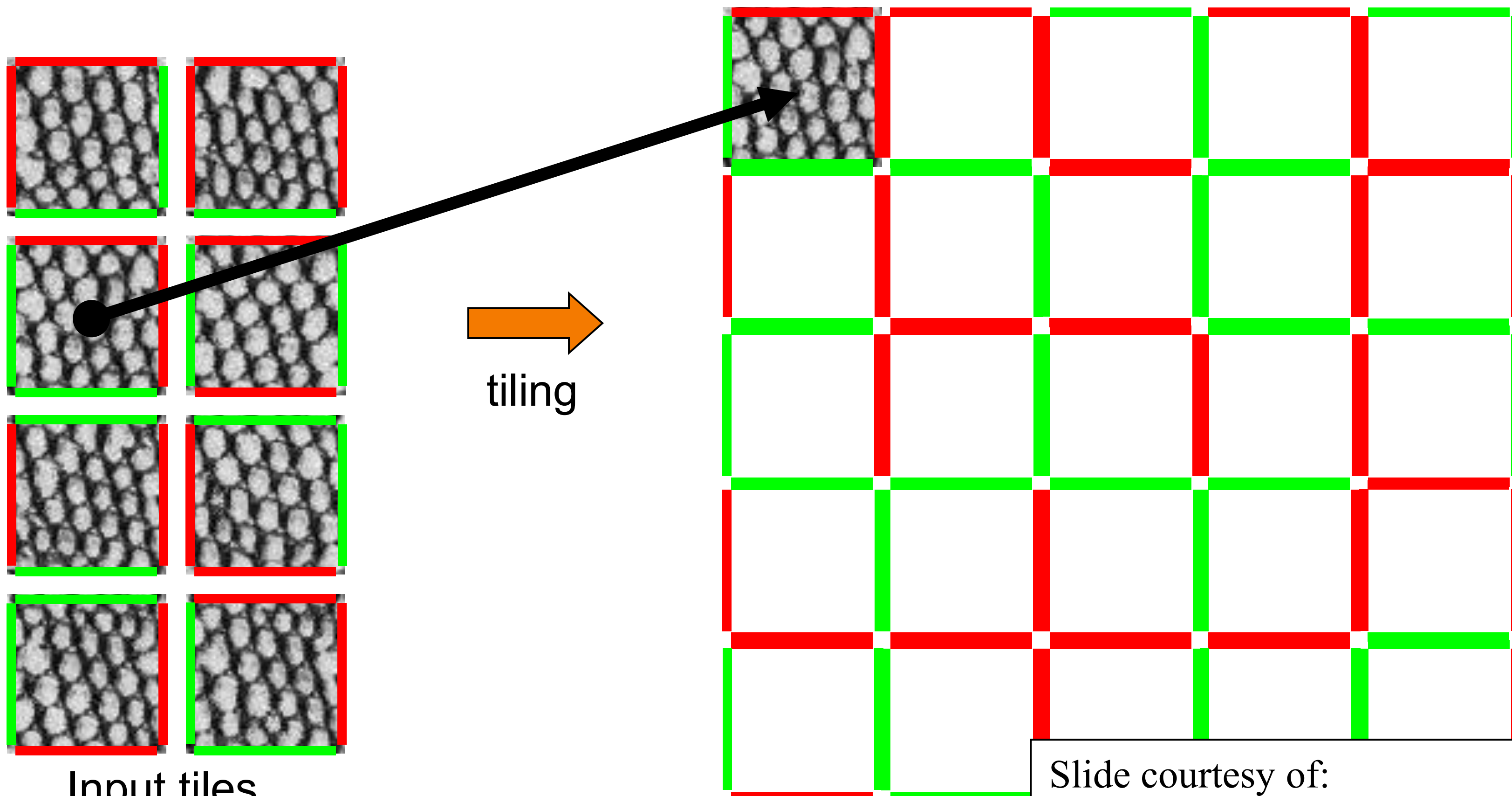

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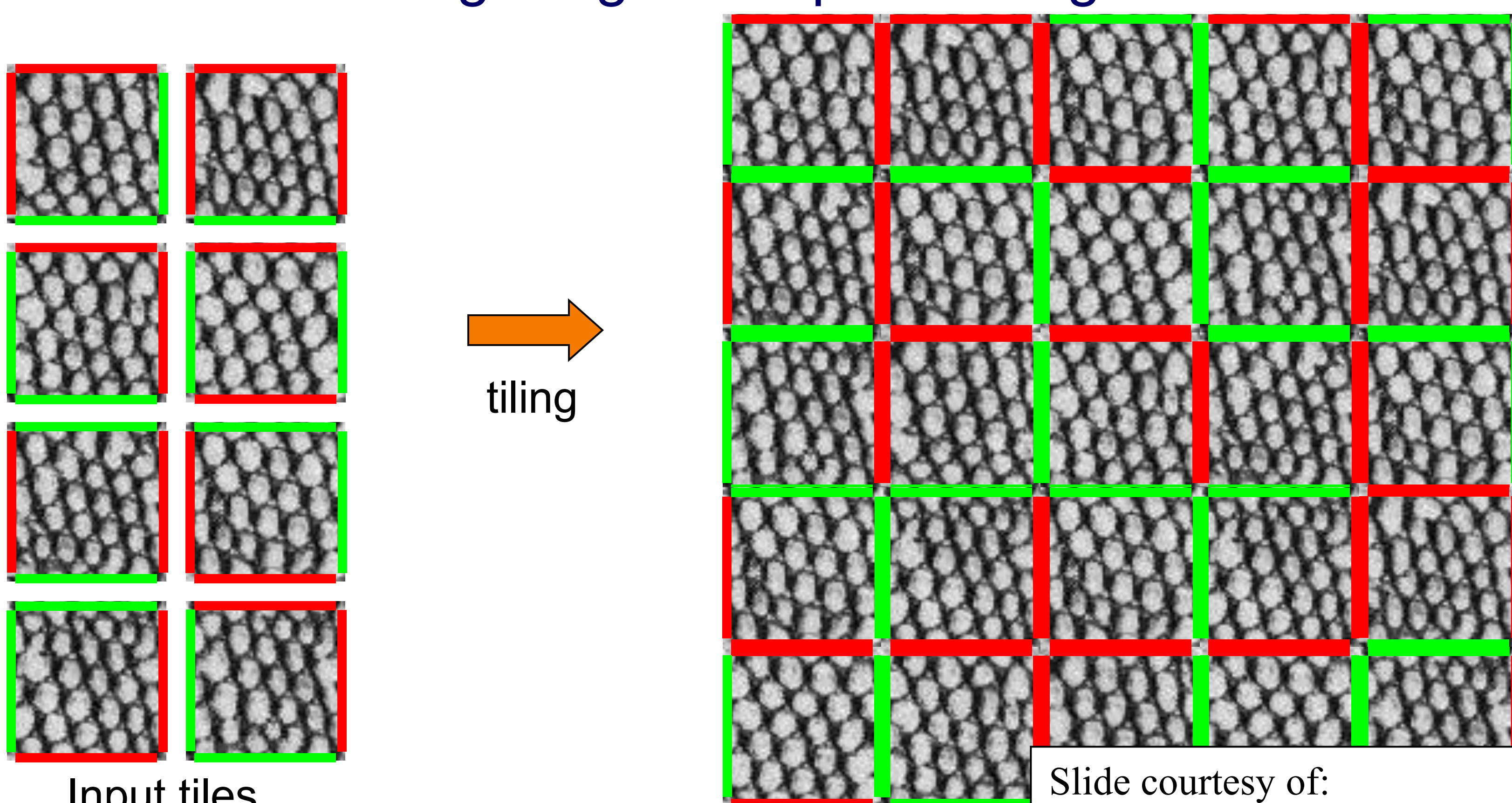

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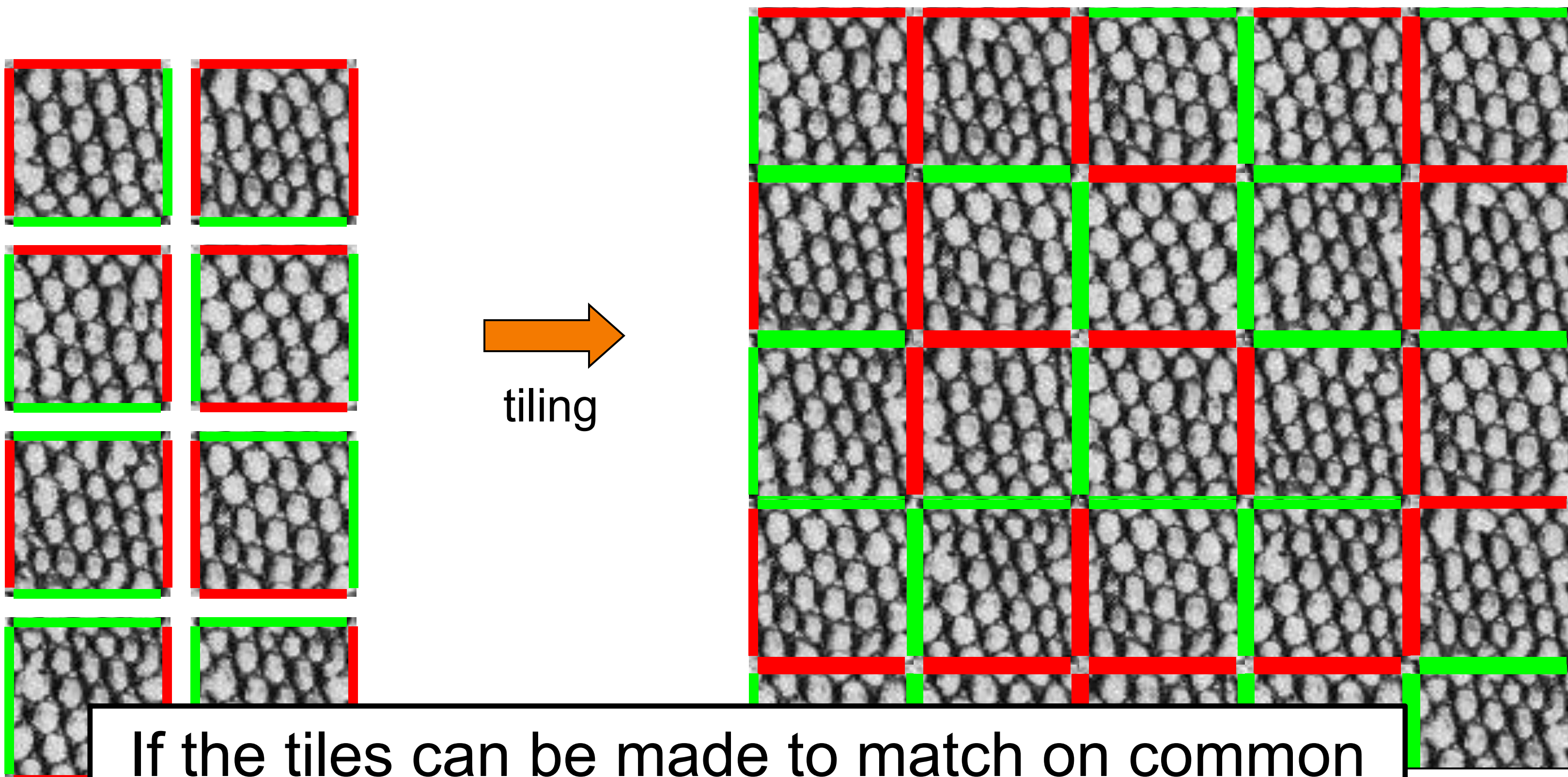


If the tiles can be made to match on common color edges, the texture will be seamless.

shardware.org

Wang Tiles

Tile Complexity:

For the texture not to appear repetitive, we need to have (random) choice in which tile we choose.

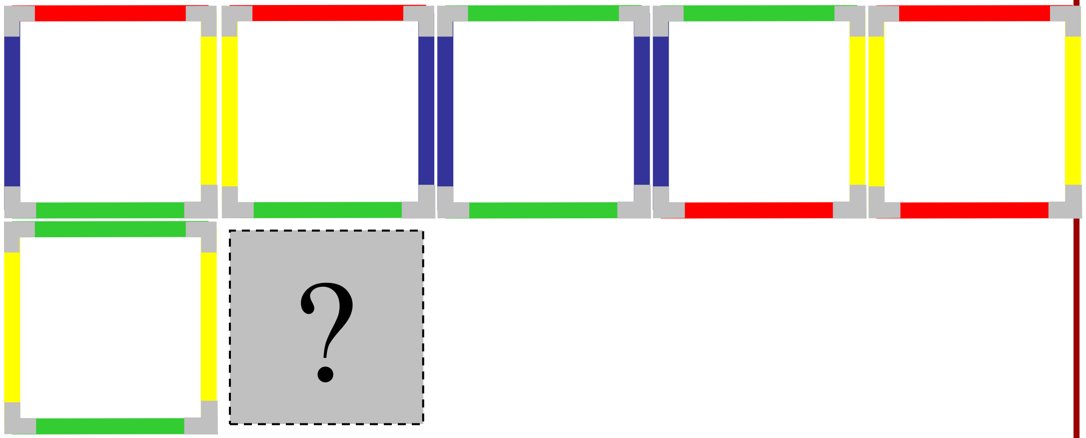
How many tiles do we need, assuming k different colors on the edges?

Wang Tiles

Tile Complexity:

In general, we have two restrictions when we introduce a new tile – the colors of the West and North edges.

Tiled Image



Wang Tiles

<u>Tile Complexity</u>:

In general, we have two restrictions when we introduce a new tile – the colors of the West and North edges.

For k colors, this means that we need to have at least k^2 tiles to be able to find one that will fit.

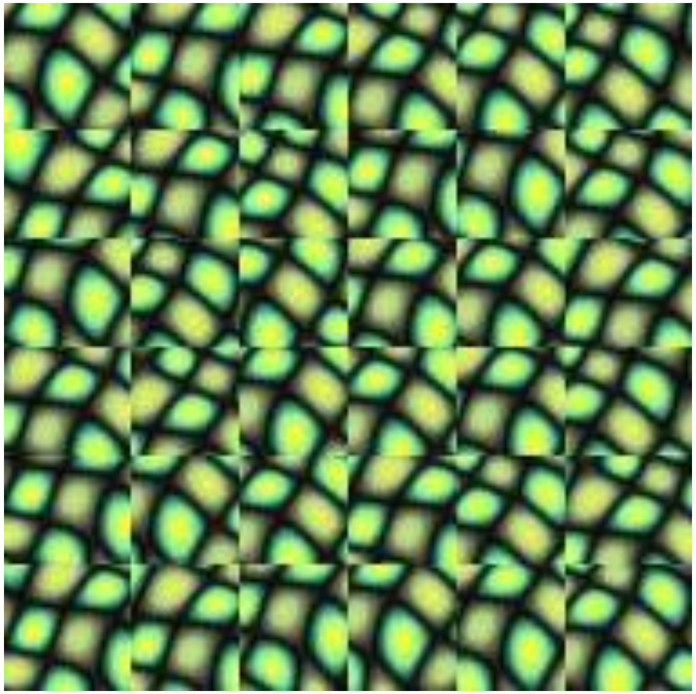
To be able to make a random choice each time, we need to have at least $2k^2$ tiles.

Wang Tiles

Tile Generation:

To generate seamless textures, tiles must match on common color edges.

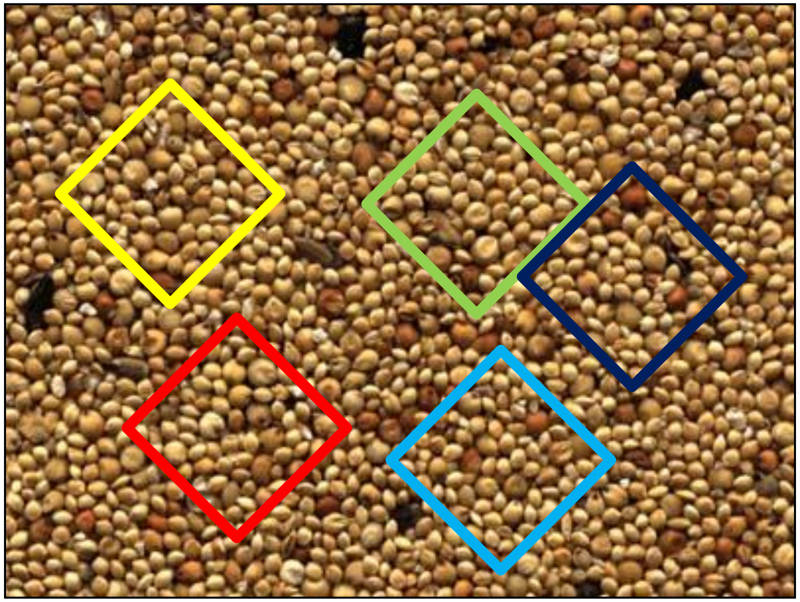
Otherwise get apparent discontinuity seams



Wang Tiles

Tile Generation:

- Associate a source diamond to each colored edge

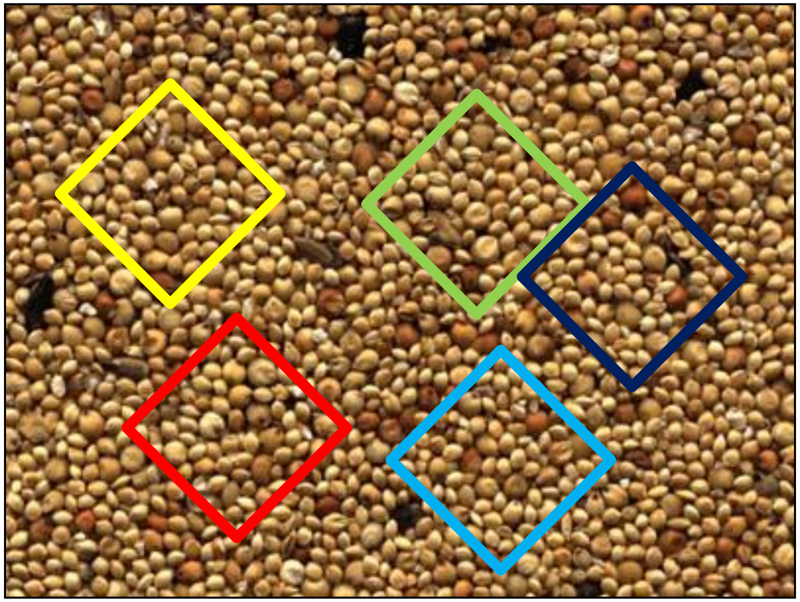


Source

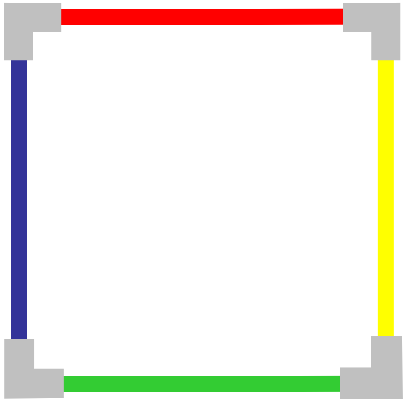
Wang Tiles

Tile Generation:

- Associate a source diamond to each colored edge
- Given a tile, paste the diamonds onto the edges



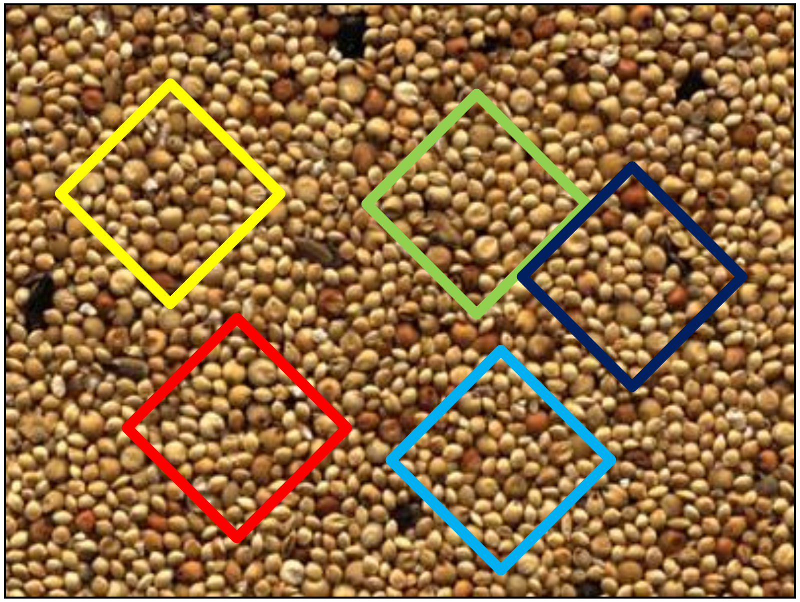
Source



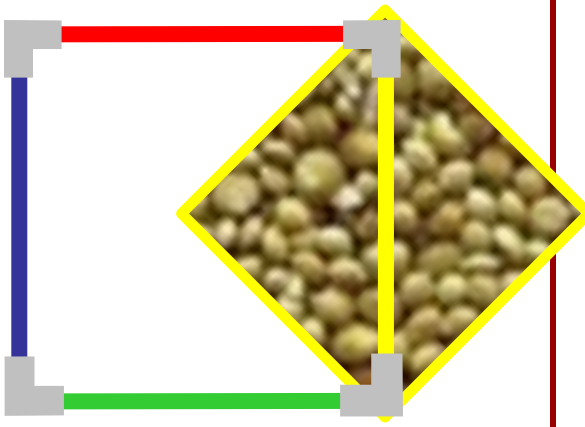
Wang Tiles

Tile Generation:

- Associate a source diamond to each colored edge
- Given a tile, paste the diamonds onto the edges



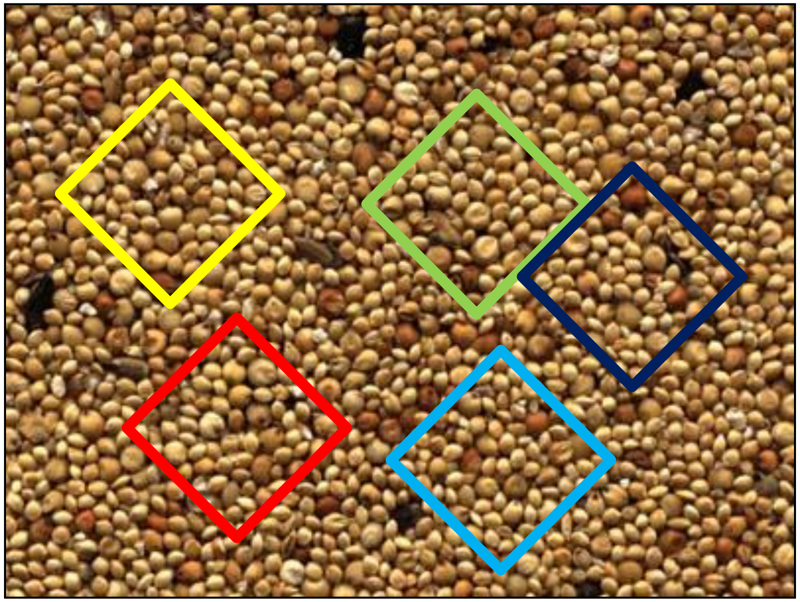
Source



Wang Tiles

Tile Generation:

- Associate a source diamond to each colored edge
- Given a tile, paste the diamonds onto the edges



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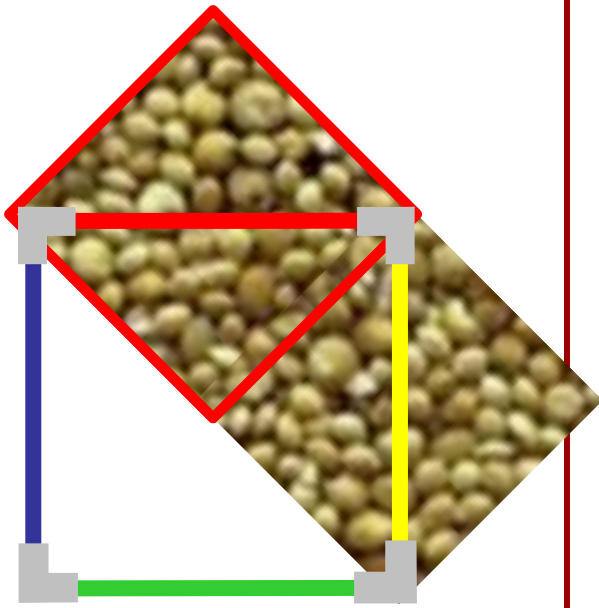
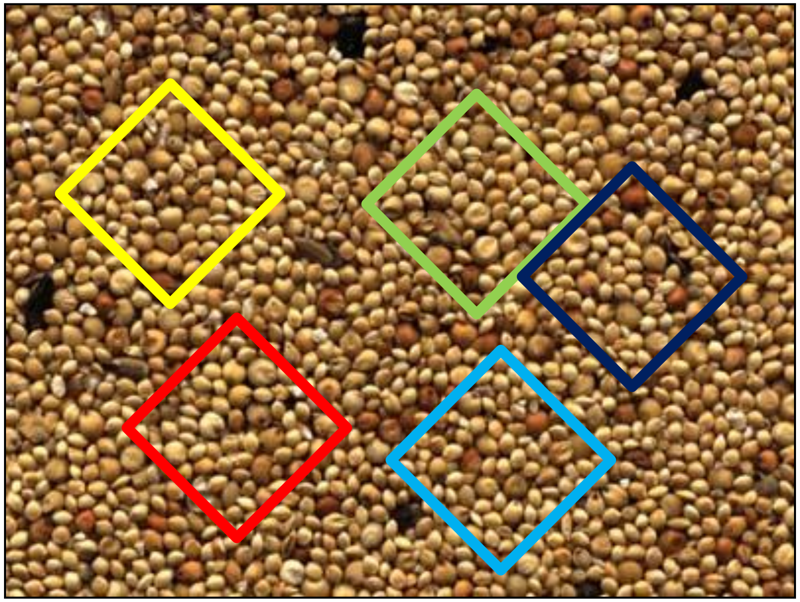


Wang Tiles

<u>Tile Generation</u>:

- Associate a source diamond to each colored edge
- Given a tile, paste the diamonds onto the edges



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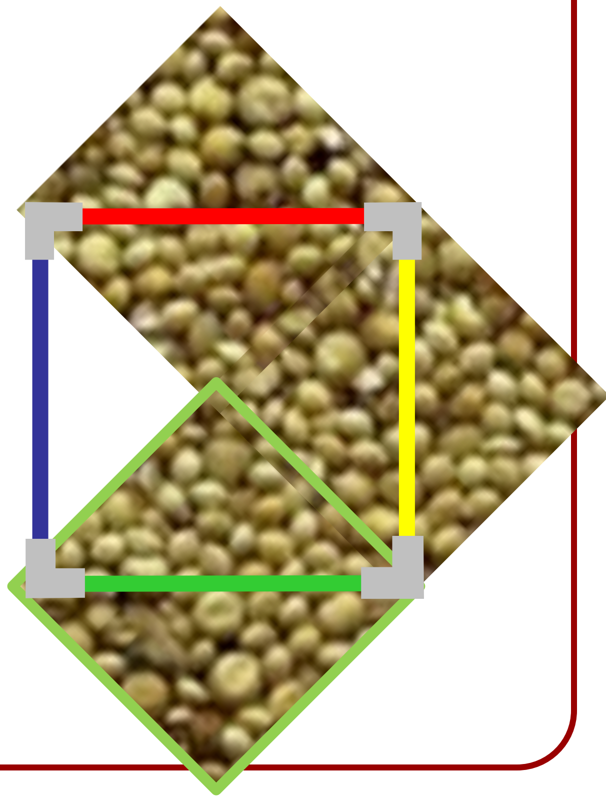
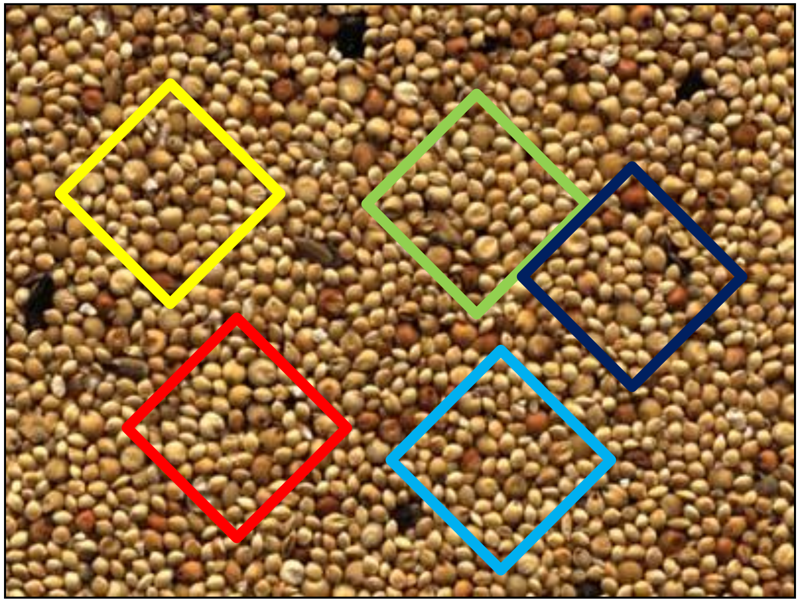


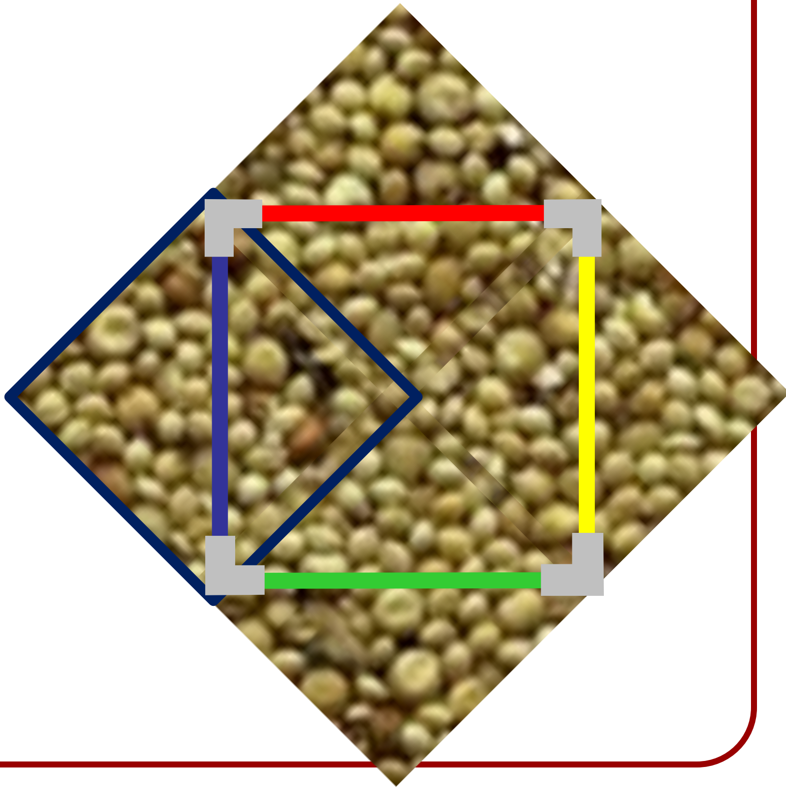
Wang Tiles

<u>Tile Generation</u>:

- Associate a source diamond to each colored edge
- Given a tile, paste the diamonds onto the edges



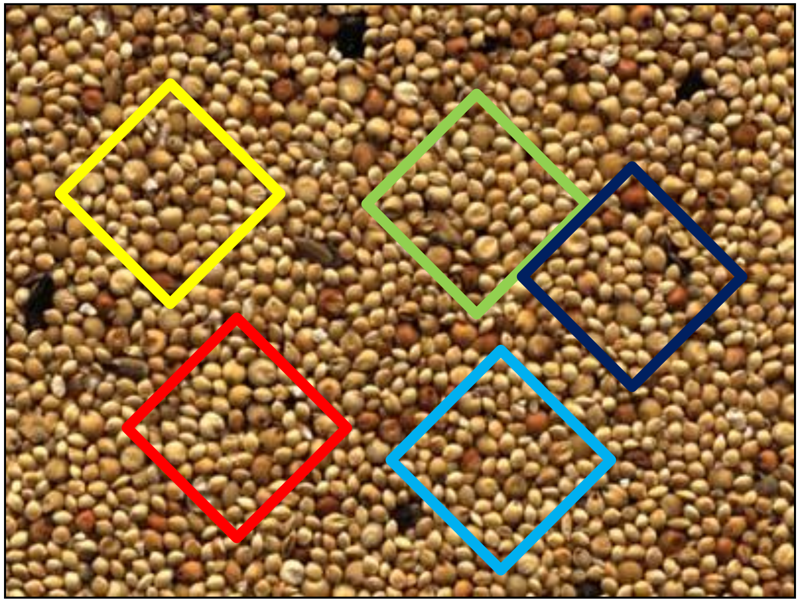
Source



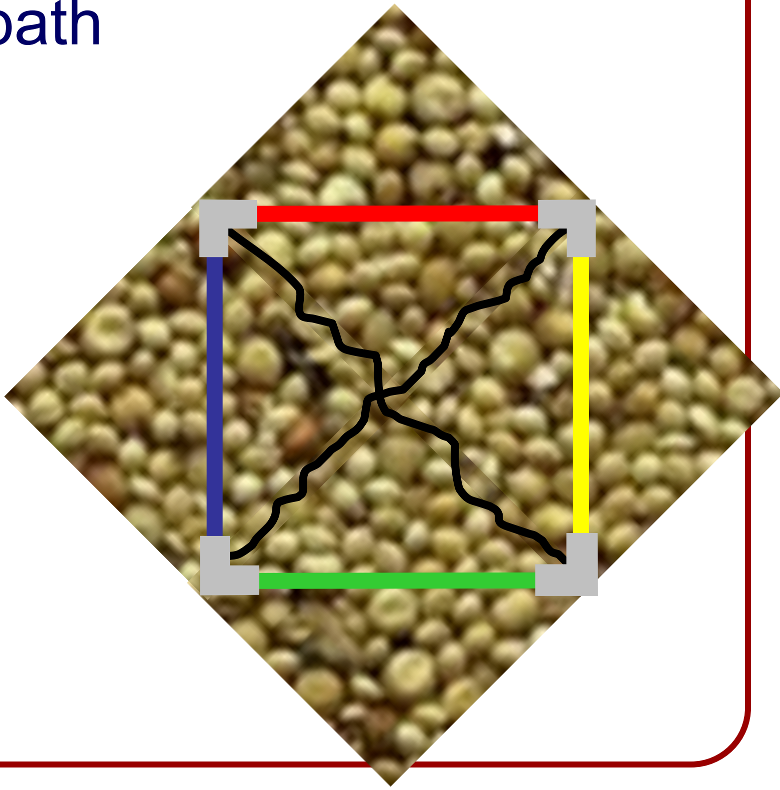
Wang Tiles

Tile Generation:

- Associate a source diamond to each colored edge
- Given a tile, paste the diamonds onto the edges
- Quilt the overlap region by solving a graph-cut problem for the minimum discontinuity path



Source

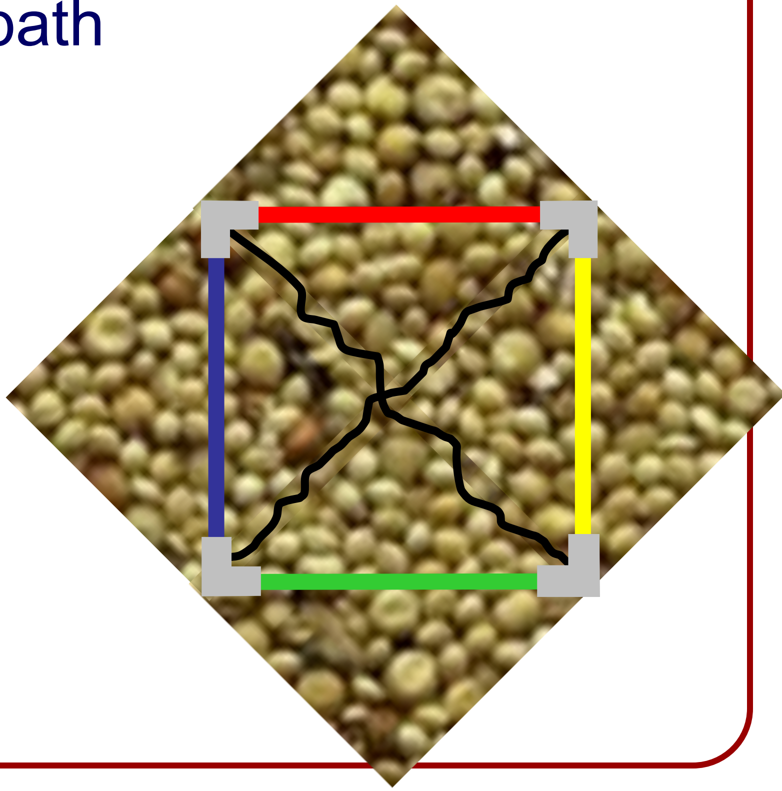


Wang Tiles

<u>Tile Generation</u>:

- Associate a source diamond to each colored edge
- Given a tile, paste the diamonds onto the edges
- Quilt the overlap region by solving a graph-cut problem for the minimum discontinuity path

Since the two-sides of an edge come from the same diamond, they are guaranteed to meet seamlessly!



Outline

- Texture Synthesis
- Midterm Info

Midterm

<u>Content</u>:

Everything that we have covered up to this point:

- Image Processing
- Sampling
- Ray-Casting/Tracing
- Illumination
- Clipping
- Texture Mapping
- Texture Synthesis

Midterm

Format:

- Closed book
- Short answer questions only
- No essays
- No true/false
- No multiple choice
- In person

Midterm

Breakdown:

Six Sections:

- Image Processing
- Sampling
- Ray Tracing
- Illumination
- Texture Mapping
- Miscellany