Perceptually-Driven Statistical Texture Modeling

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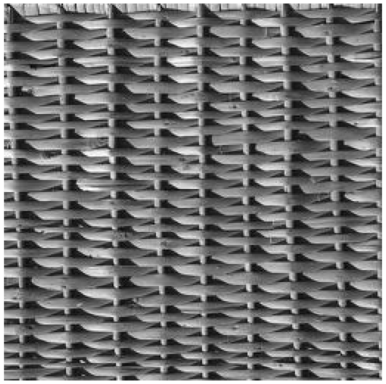
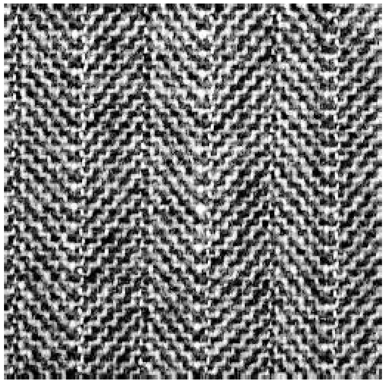
What is “Visual Texture”?

Homogeneous, with repeated structures....

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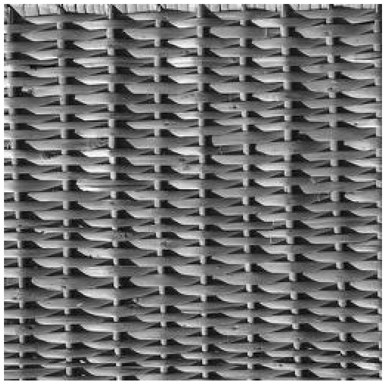
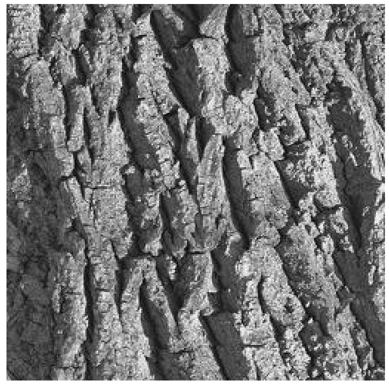
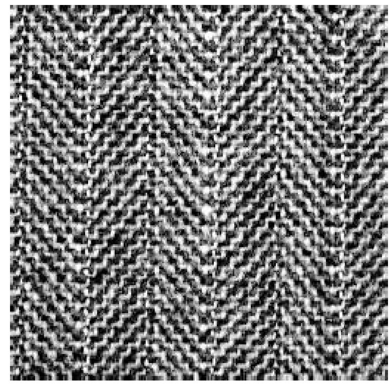
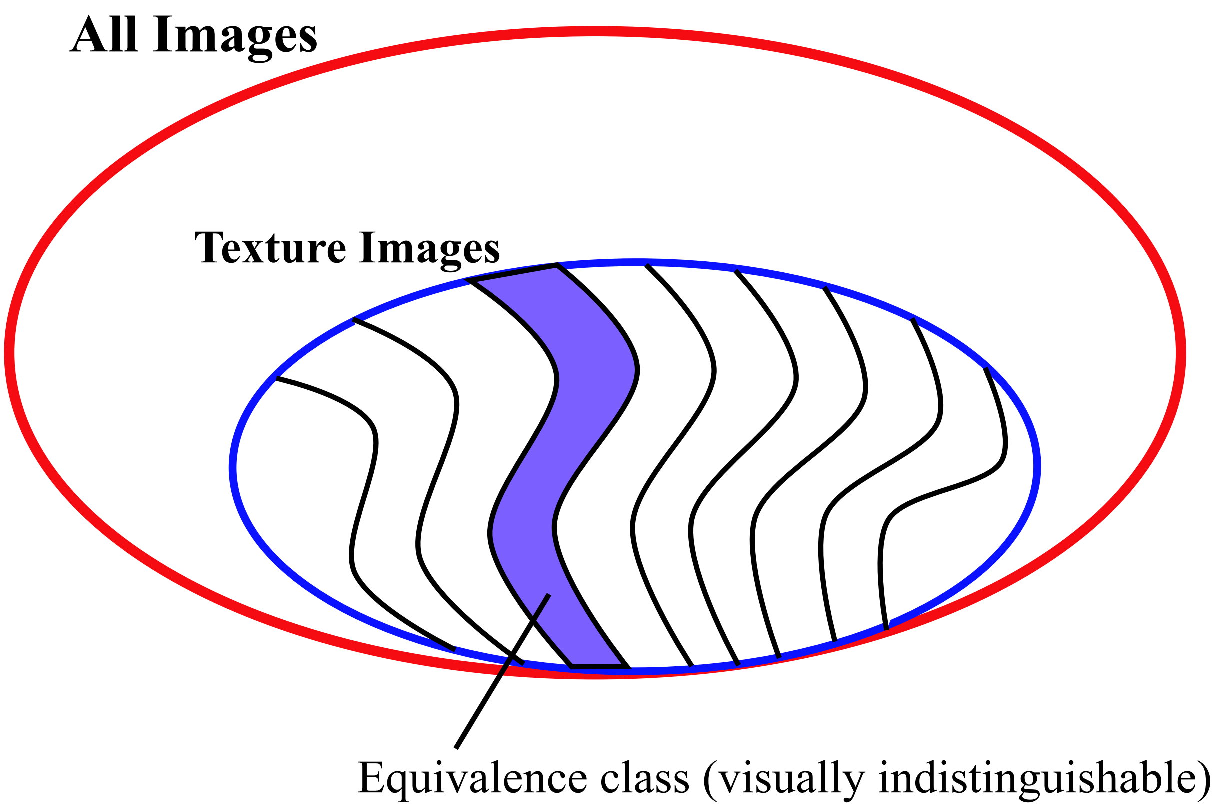





Homogeneous, with repeated structures....

“You know it when you see it”

Perceptual Texture Description



Perceptual model:

- Set of texture images divided into equivalence classes (metamers)
- Perceptual "distance" between classes

Julesz's Conjecture (1962)

Hypothesis: two textures with identical Nth-order pixel statistics look the same (for some N).

- Explicit goal of capturing perceptual definition with a statistical model
- Statistical measurements should be:
  - universal (for all textures)
  - stationary (translation-invariant)
  - a minimal set (necessary and sufficient)
- Julesz (and others) constructed counter-examples for N=2 and N=3, dismissing the hypothesis...

Julesz's Conjecture, Revisited

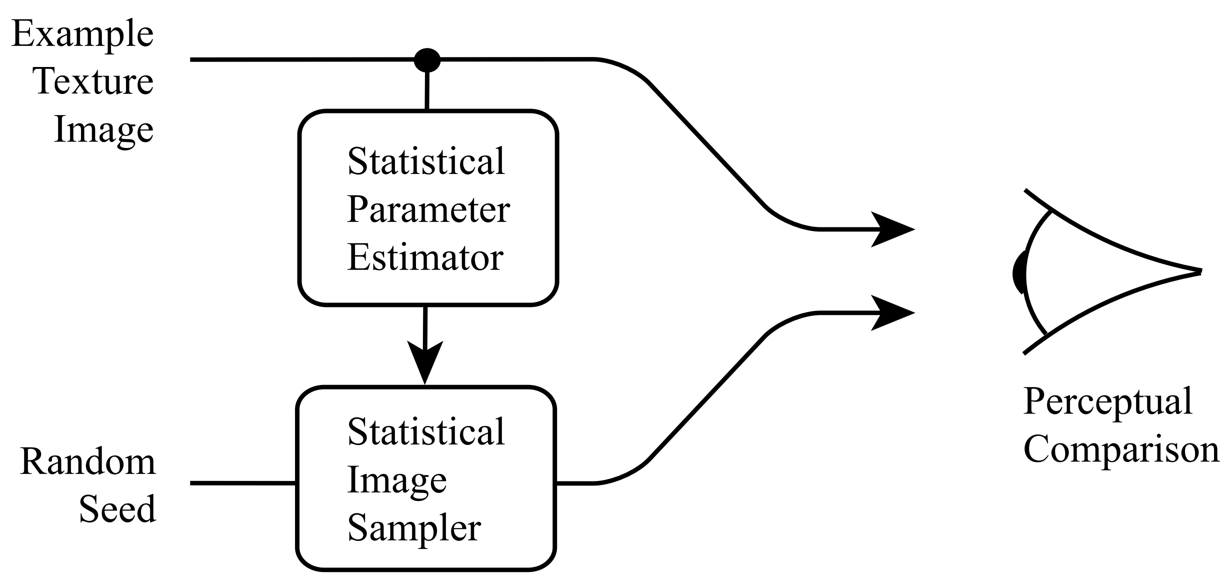
Why did the early attempts fail?

- Right hypothesis, wrong model: A set of measurements equivalent to the visual processes used for texture perception should satisfy the hypothesis.
- Lacked a powerful methodology for testing whether a model satisfies the hypothesis
- We can benefit from advances of the past few decades:
  - scientific: better understanding of early vision
  - engineering/mathematical: "wavelets", statistical estimation, statistical sampling
  - technological: availability of powerful computers, digital images

Testing a Texture Model

- As with most scientific test, we seek counter-examples
- Fundamental problem: we usually work with a small number of examples (tens or hundreds).
- Classification is an important application, but a weak test
- Synthesis can provide a much stronger test...

Testing a Model via Synthesis

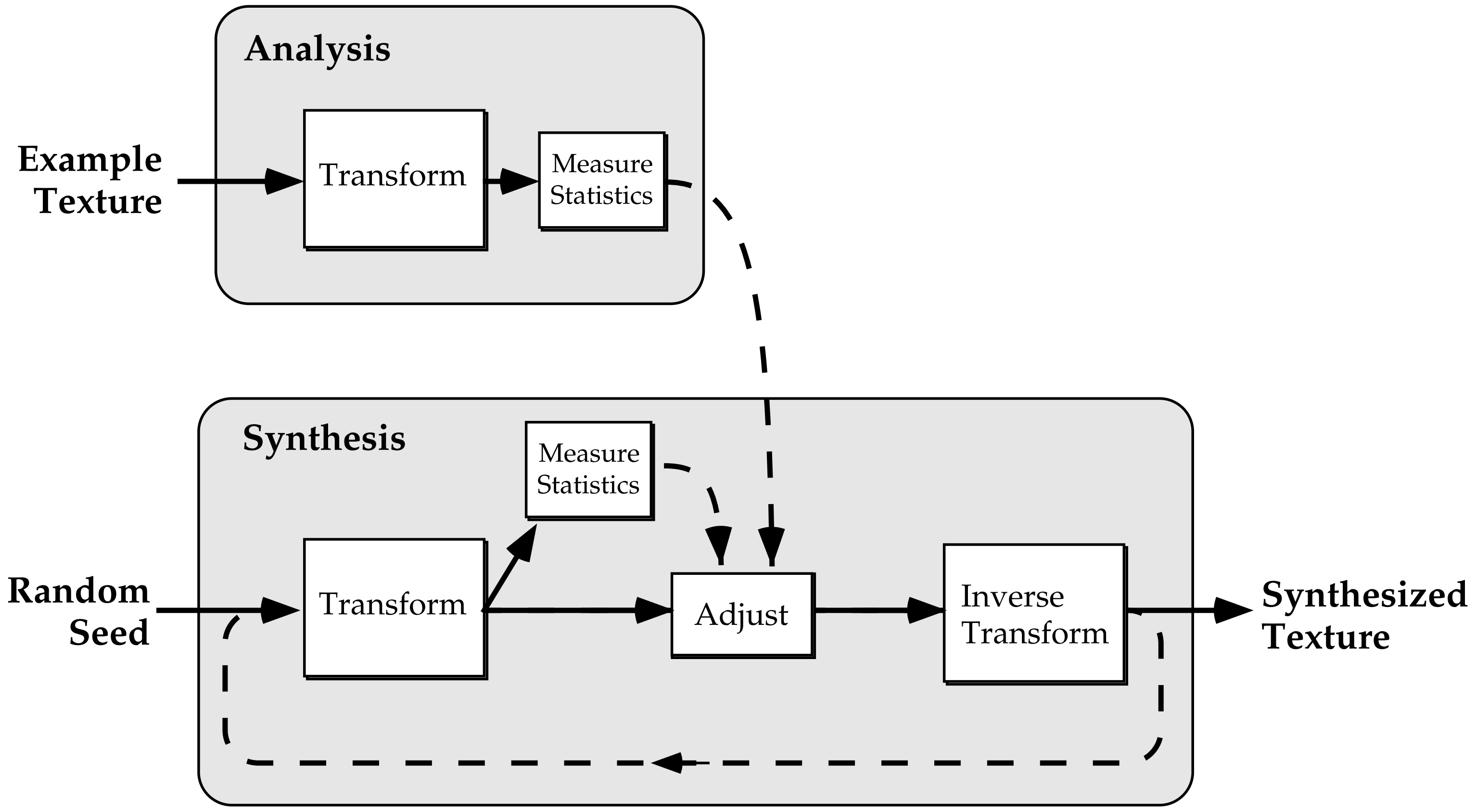


- Positive results are compelling, assuming:
  - reference texture set contains a sufficient variety
  - statistical sampler generates "typical" examples
- Negative results are definitive: A single failure indicates insufficiency of constraints!
- Partial necessity test: remove a constraint and find a failure example
- Studying failures allows us to refine the model

Methodological Ingredients

1. Representative set of example texture images: Brodatz, VisTex, our own
2. Method of estimating parameters: sample mean
3. Method of generating sample images from model: primary topic of this work
4. Perceptual test: informal viewing

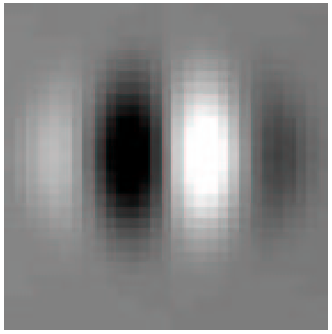
Iterative Synthesis Algorithm



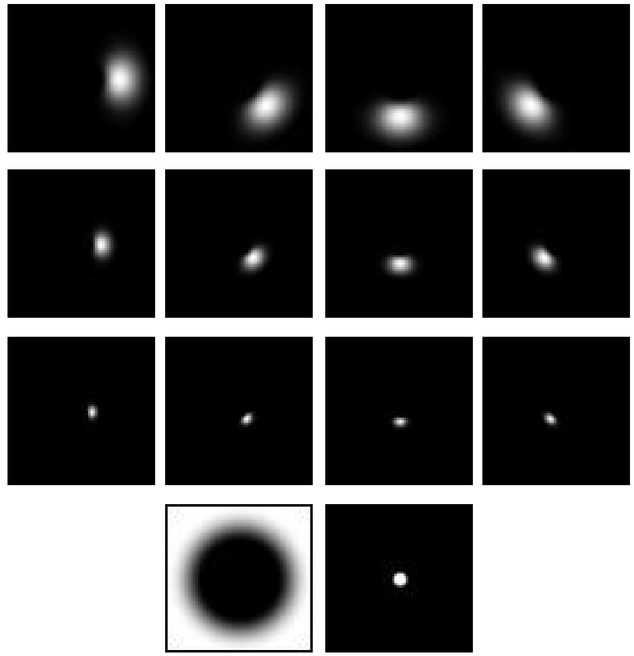
Heeger & Bergen, ’95

Transform: Steerable Pyramid

Example basis function



Spectra



Linear basis: multi-scale, oriented, complex.

Basis functions are oriented bandpass filters, related by translation, dilation, **rotation** (directional derivatives, order $K-1$).

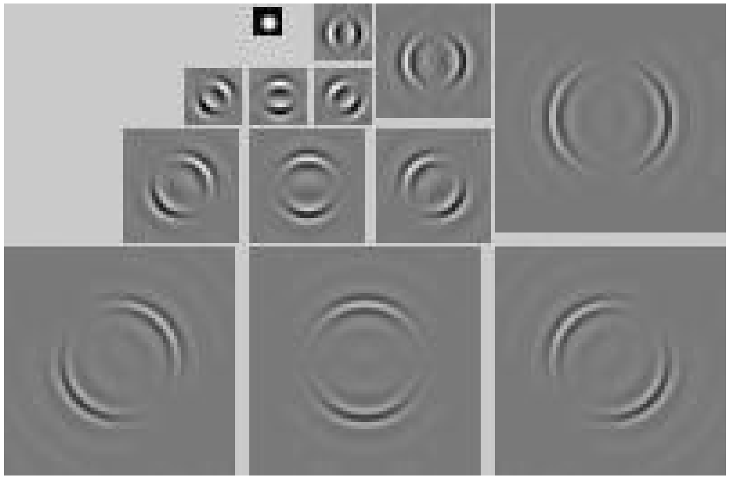
Tight frame, $4K/3$ overcompleteness for K orientations.

Translation-invariant, rotation-invariant.

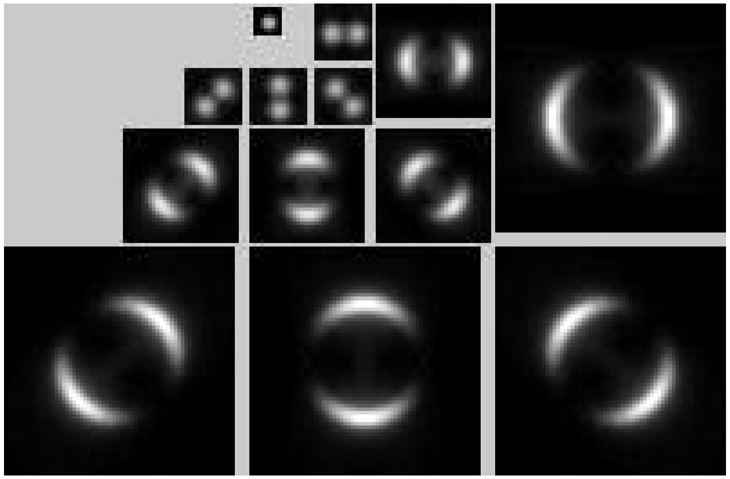
Motivation: image processing, computer vision, biological vision.

Steerable Pyramid: Example Decomposition

Real part of coefficients



complex magnitude of coefficients



Decomposition of a “disk” image

Parameters: Marginal Statistics

Distribution of intensity values is captured with the first through fourth moments of both the pixels and the lowpass coefficients at each pyramid scale.

Note: A number of authors have used marginal histograms:

Faugeras '80 (pixels), Heeger & Bergen '95 (wavelet), Zhu etal. '96 (Gabor).

15 parameters

Parameters: Spectral

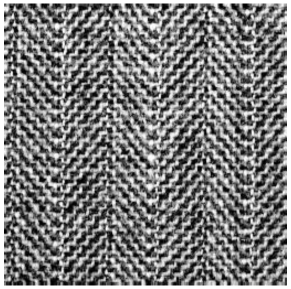
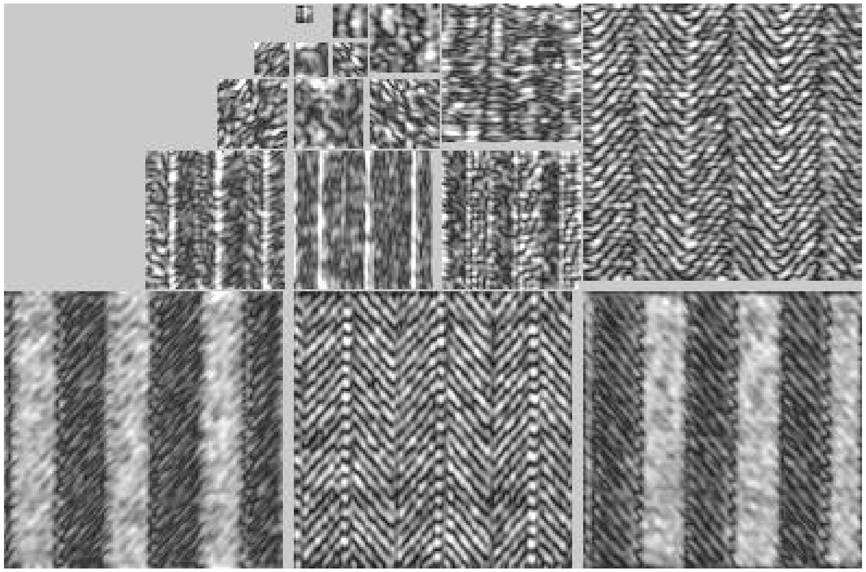
Periodicity and globally oriented structure is best captured by frequency-domain measures (Francos, '93).

Can be captured by autocorrelation measurements (included in most texture models).

In our model: central 7×7 region of the autocorrelation of each subband provides a crude measure of spectral content *within* each subband.

125 parameters

Parameters: Magnitude Correlation

Coefficient magnitudes are correlated both spatially and across bands. We capture this with local autocorrelation and cross-correlation measurements.

472 parameters

Parameters: Phase Correlation

Phases of complex responses at adjacent scales are aligned near image "features".

We capture this using a novel measure of relative phase:

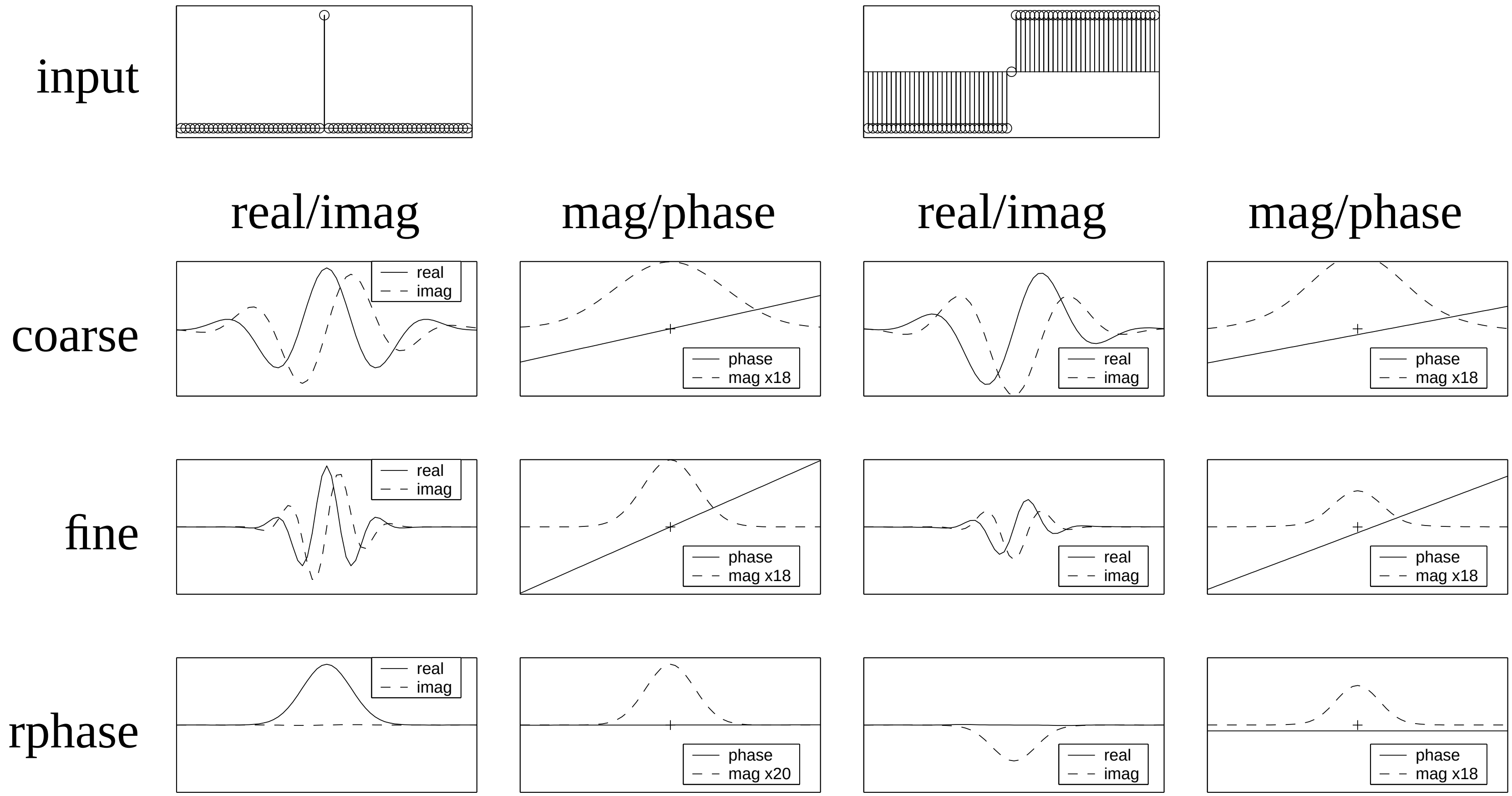
$$\phi(f,c) = \frac{c^2 \cdot f^*}{|c|},$$

where f is a fine-scale coefficient, c is a coarse-scale coefficient at the same location.

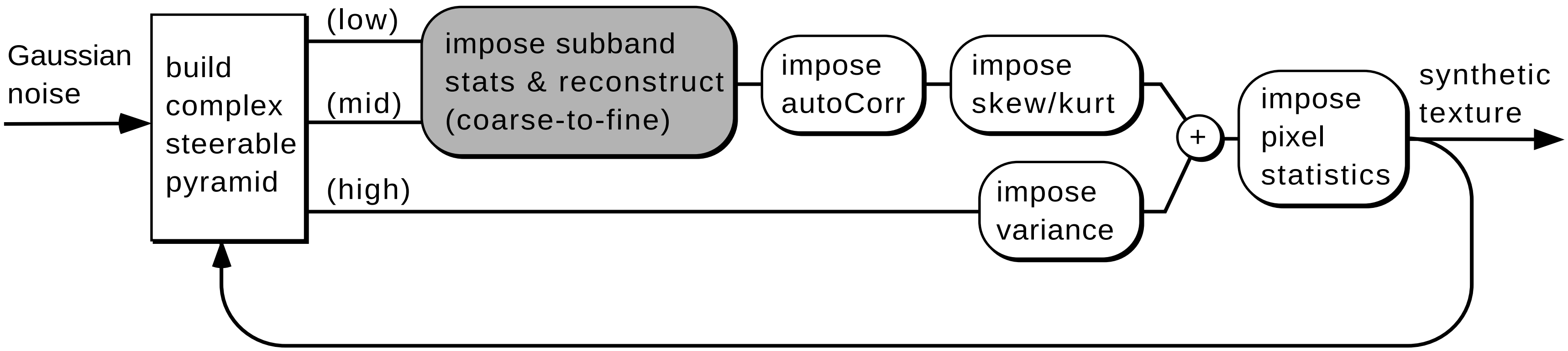
96 parameters

Total parameters: 708

Phase Correlation Example



Implementation



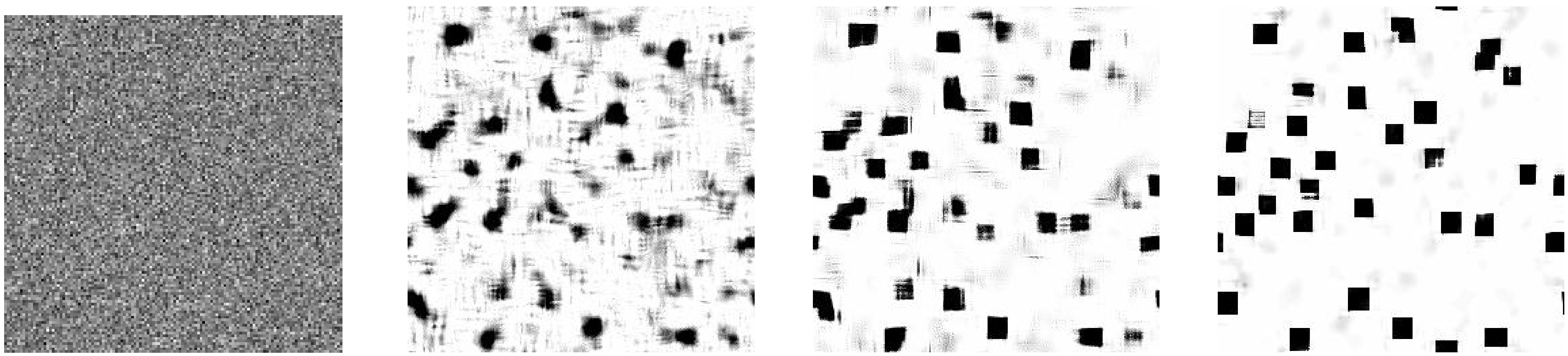
Each statistic, $\phi_k(\vec{I})$, is imposed by gradient projection:

$$\vec{I}' = \vec{I} + \lambda_k \vec{\nabla} \phi_k(I), \qquad \text{s.t. } \phi_k(\vec{I}) = m_k,$$

where m_k are the parameter values estimated from the example texture.

Example Synthesis Sequence

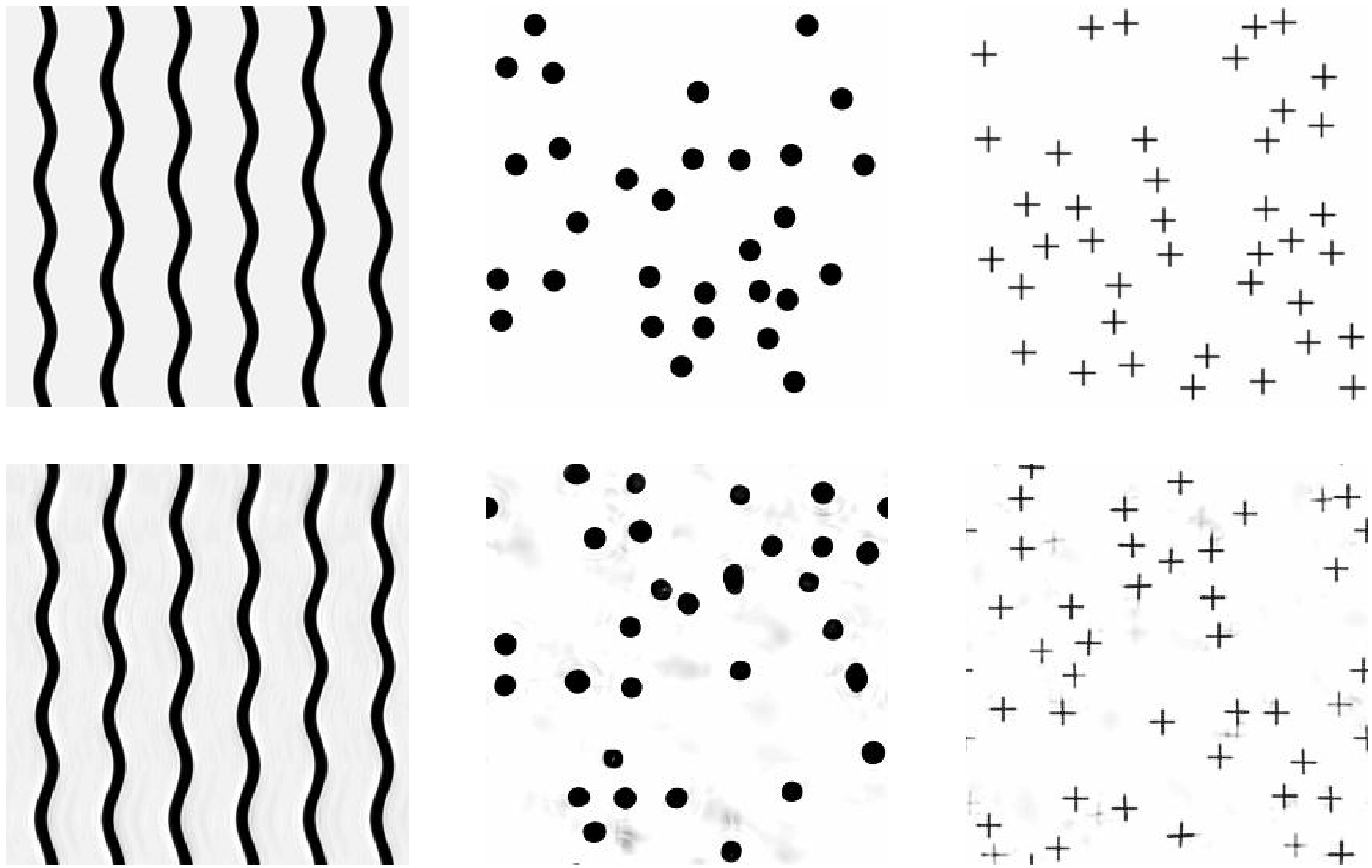
Initial | 1 | 4 | 64



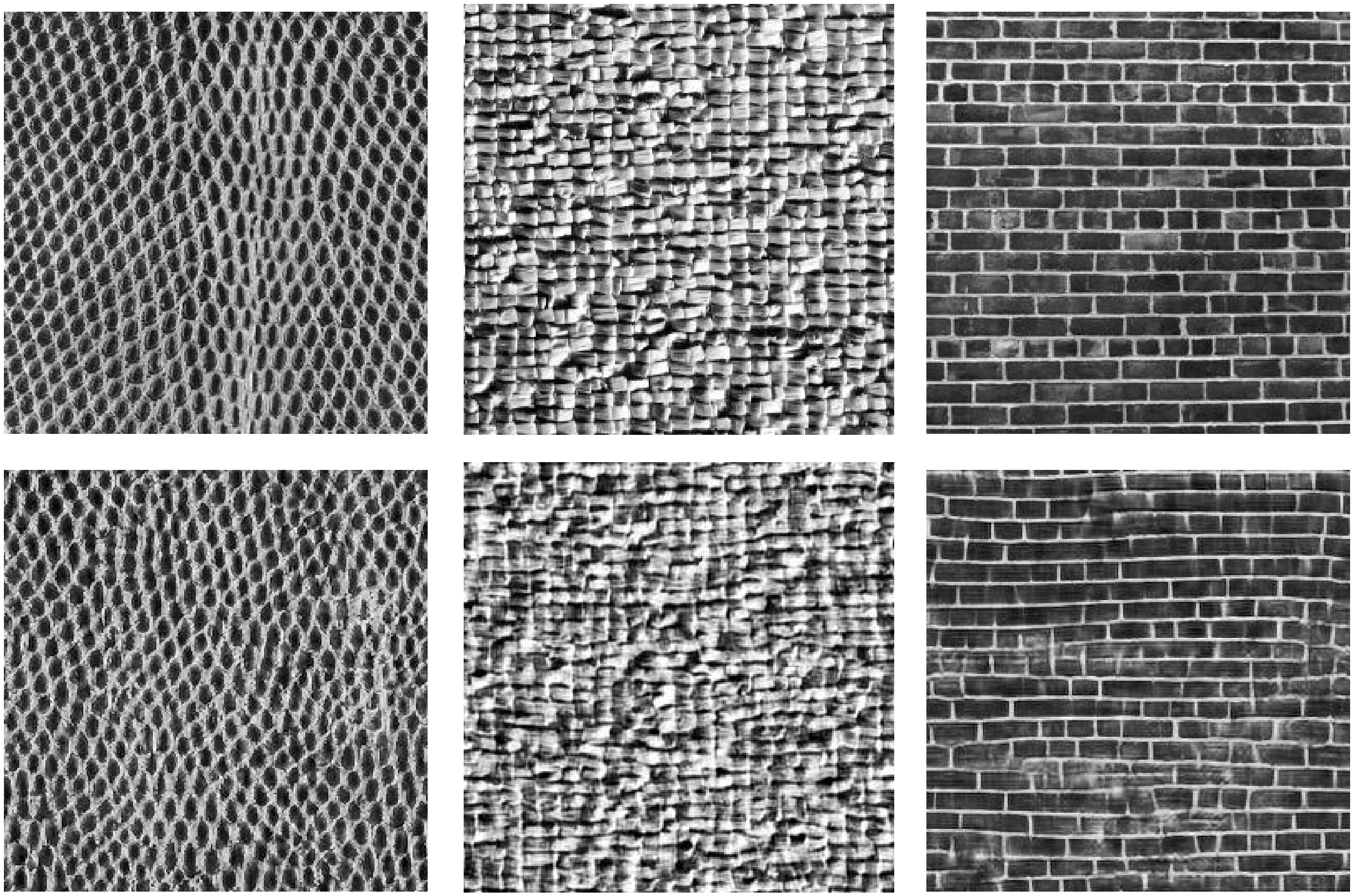
We cannot prove convergence. But in practice, algorithm converges rapidly (typical: 50 iterations).

Run time: 256×256 image takes roughly 20 minutes (500 Mhz Pentium workstation, matlab code)

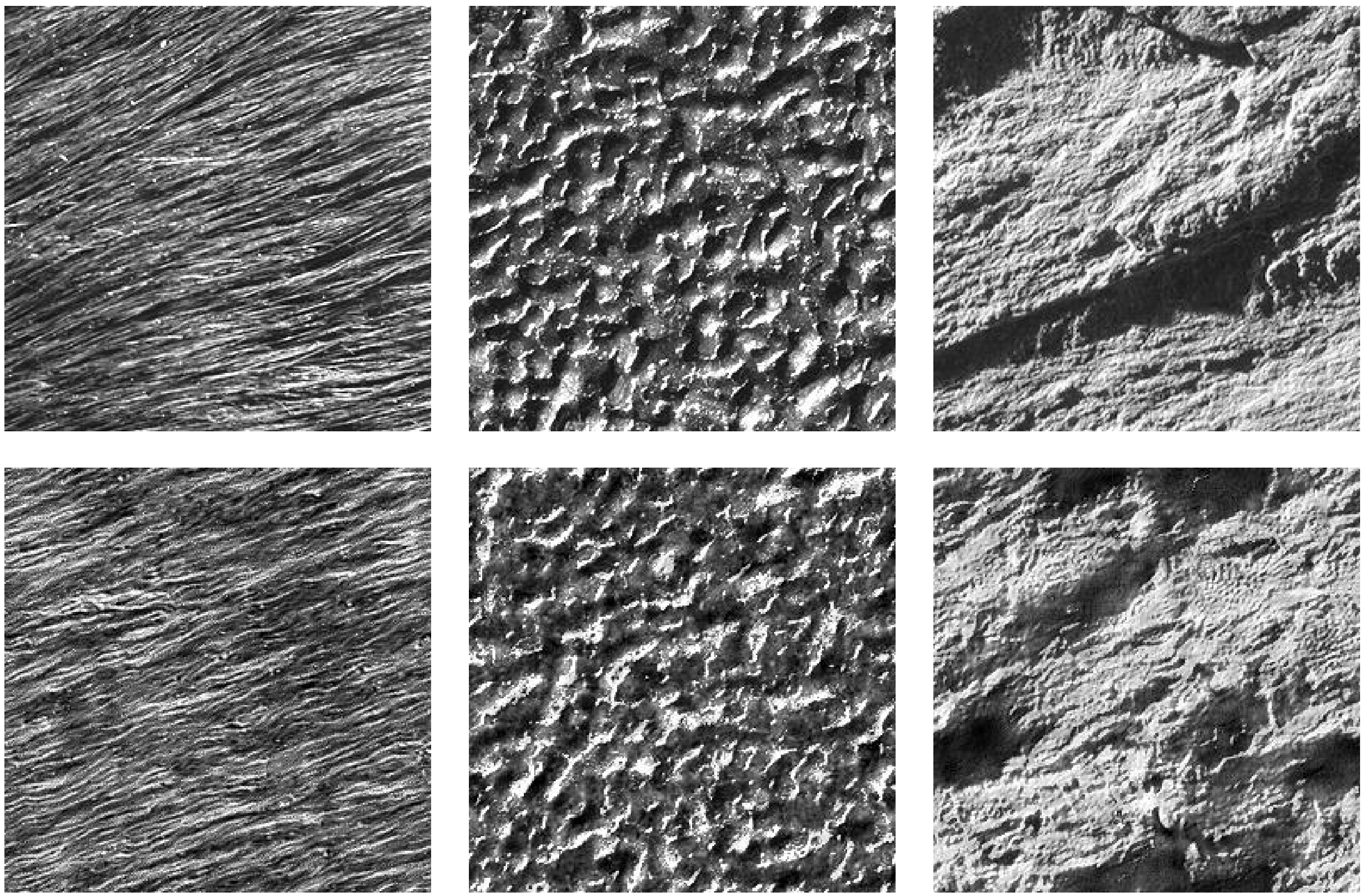
Examples: Artificial



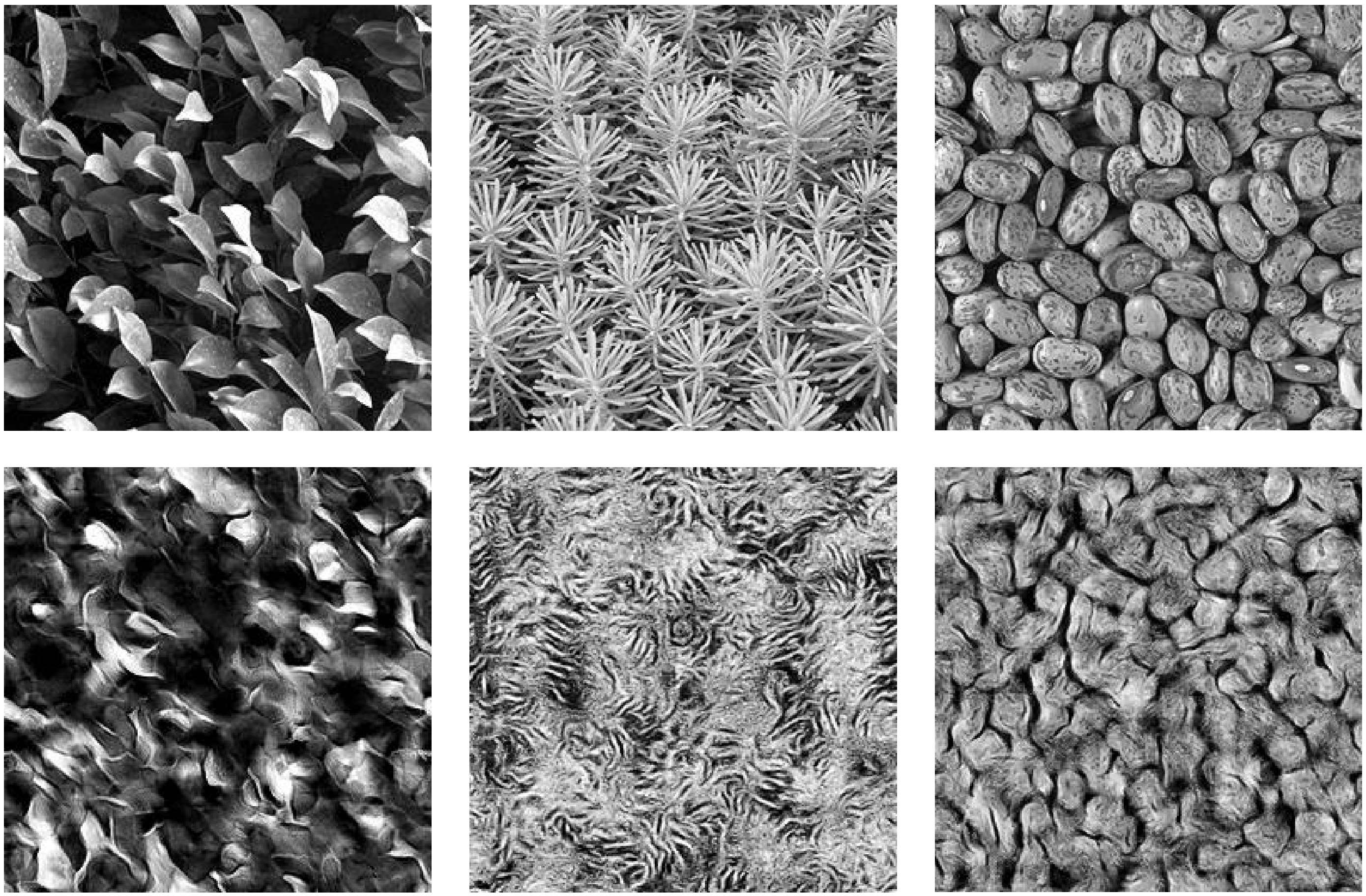
Examples: Photographic, Quasi-periodic



Examples: Photographic, Aperiodic



Examples: Photographic, Structured

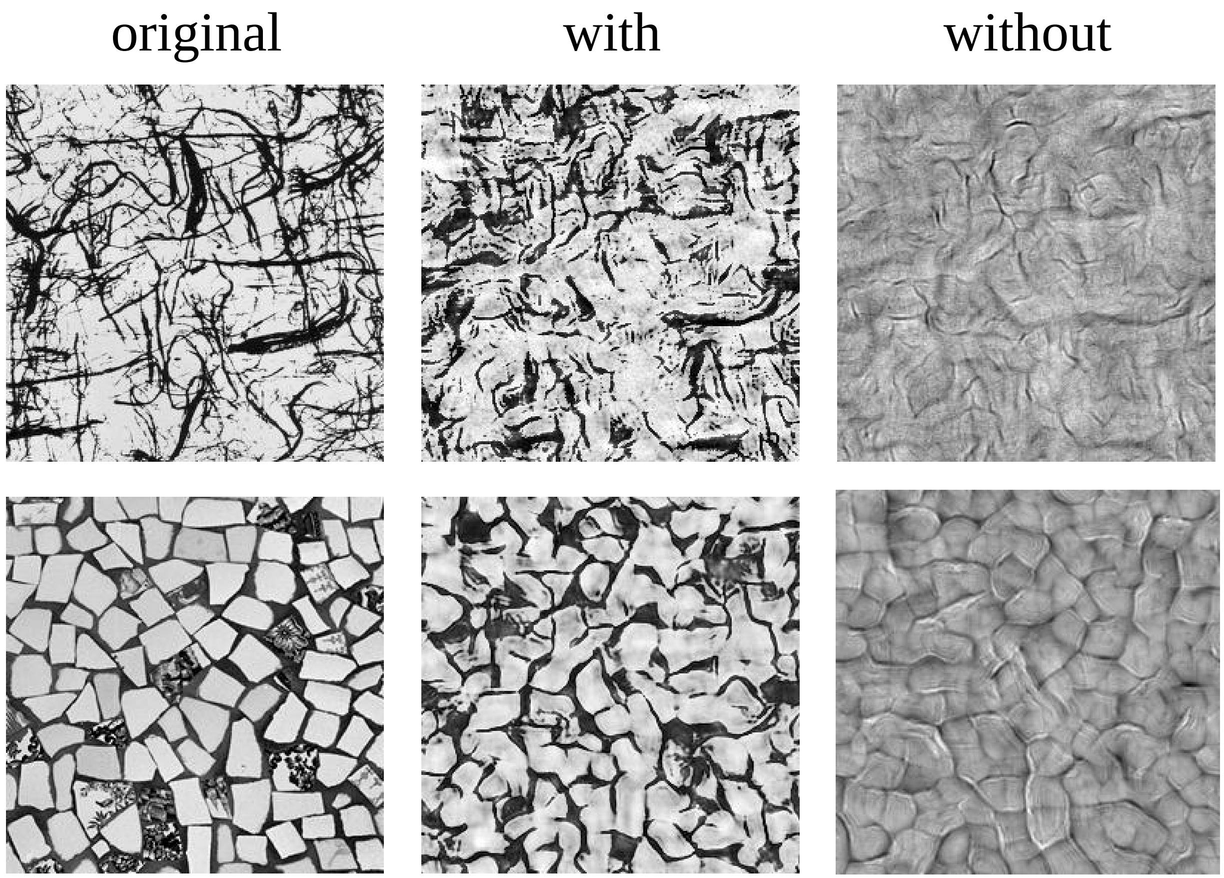


Examples: Color

Color is incorporated by transforming to YIQ space, and including cross-band magnitude correlations in the parameterization.

Examples: Non-textures?

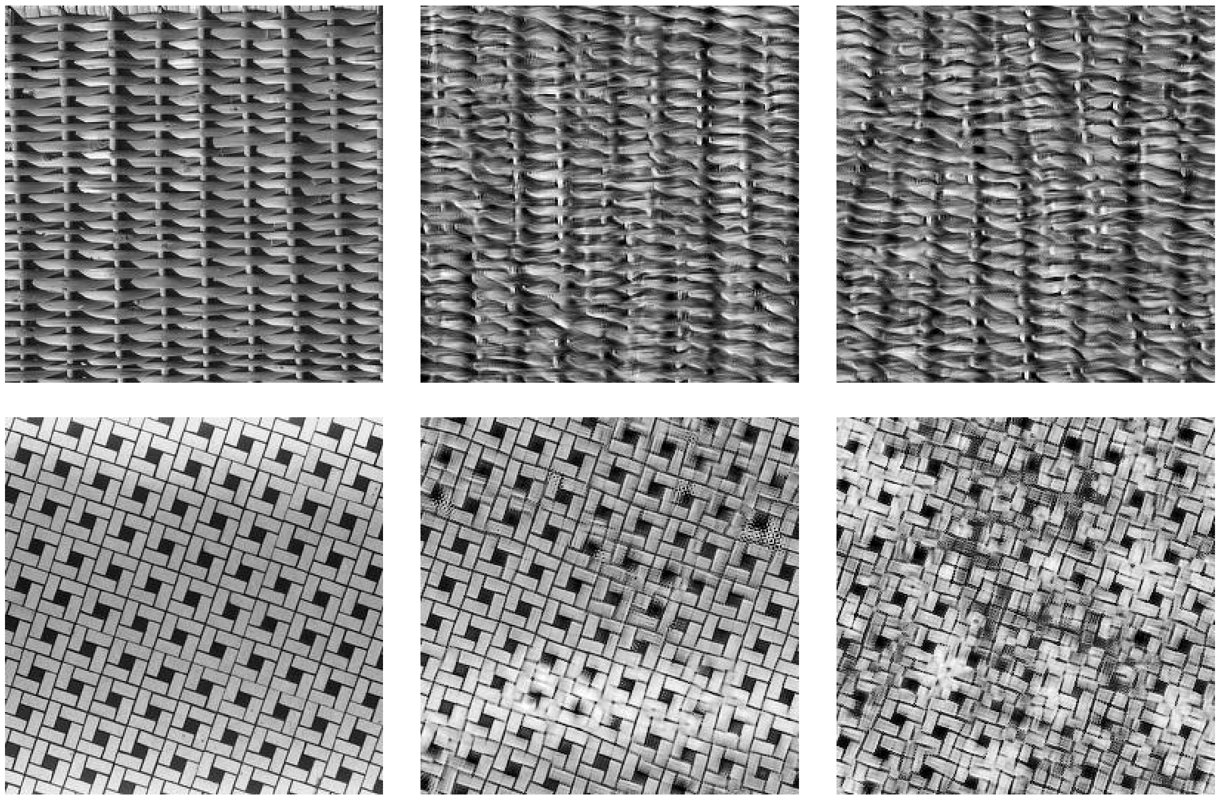
Necessity: Marginal Statistics



Needed for proper distribution of intensity values (at each scale).

Necessity: Autocorrelation

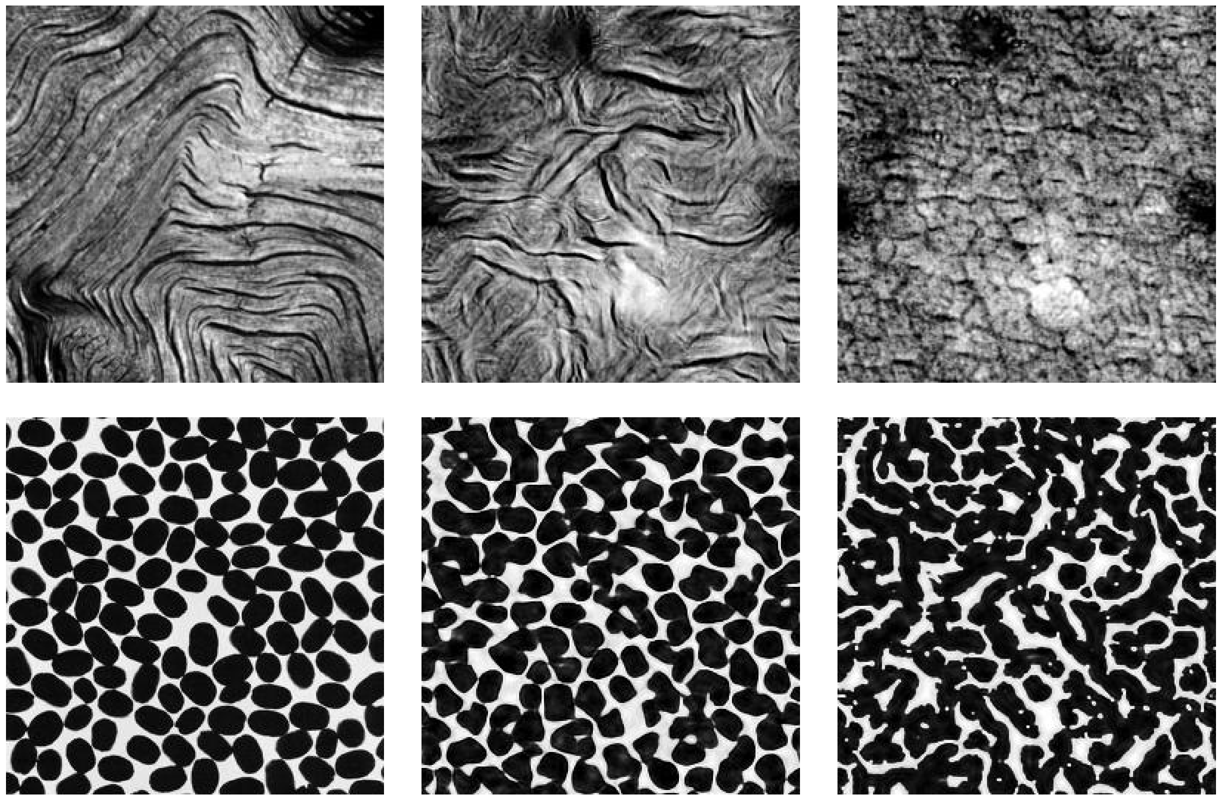
original | with | without



Needed for capturing periodicity and global orientation.

Necessity: Magnitude Correlation

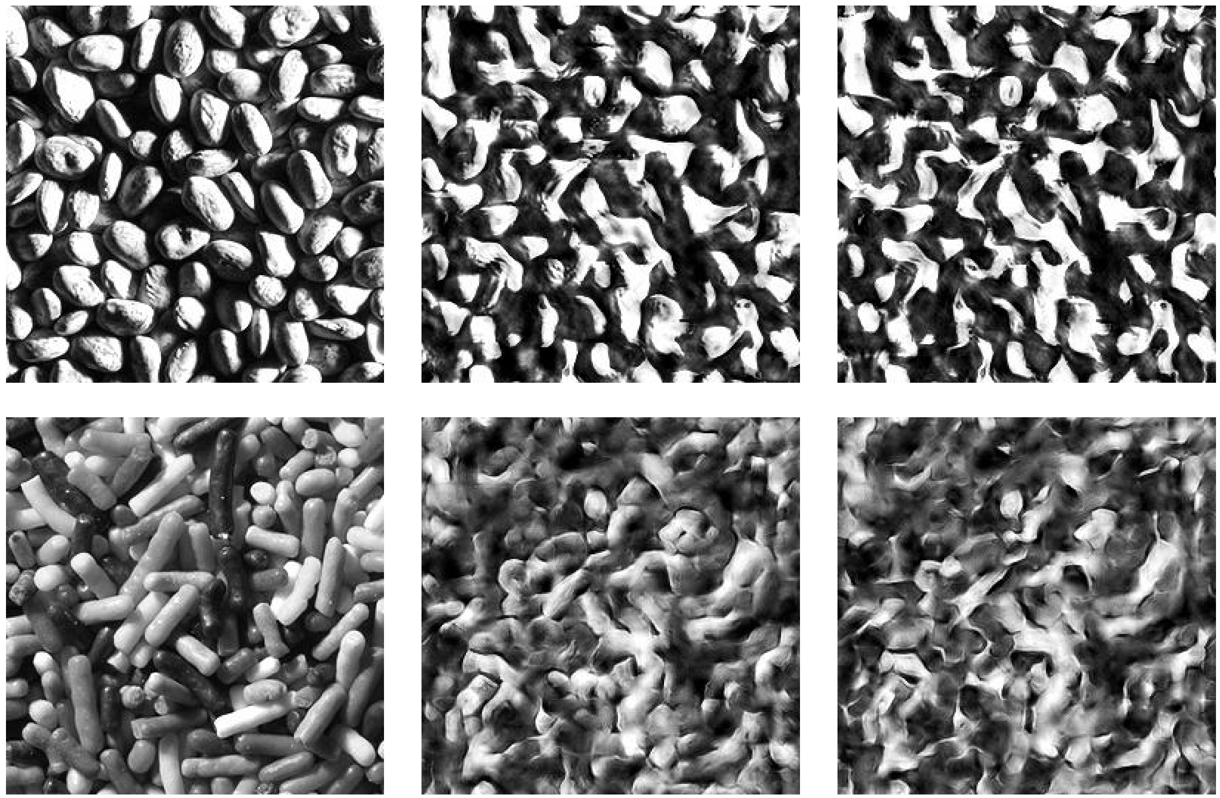
original with without



Needed for capturing periodicity local structure.

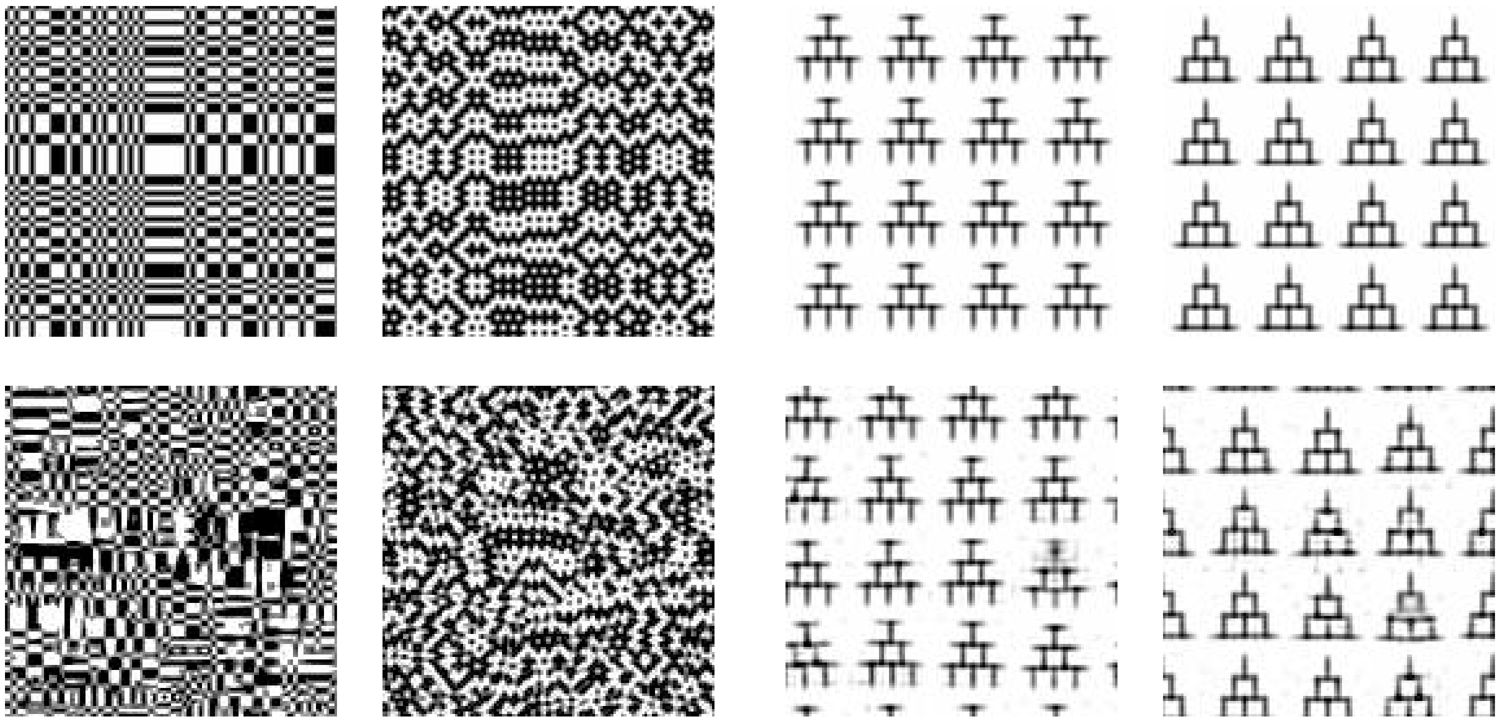
Necessity: Relative Phase

original with without



Needed for capturing details of local structure (edges vs. lines), and shading.

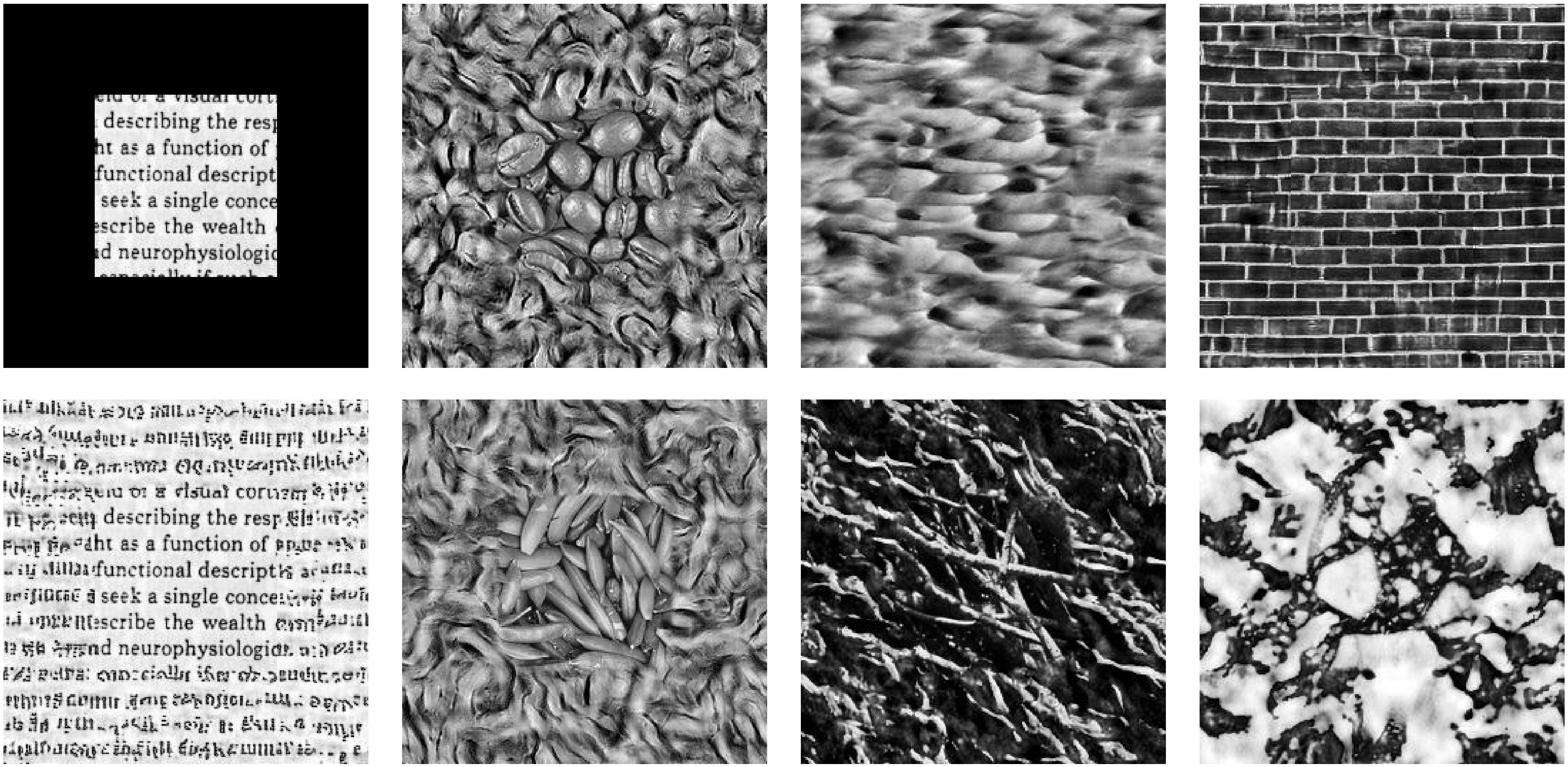
Julesz Counter-Examples



Examples with identical 3rd-order pixel statistics

Left: Julesz ’78;   Right: Yellott ’93

Spatial Extrapolation

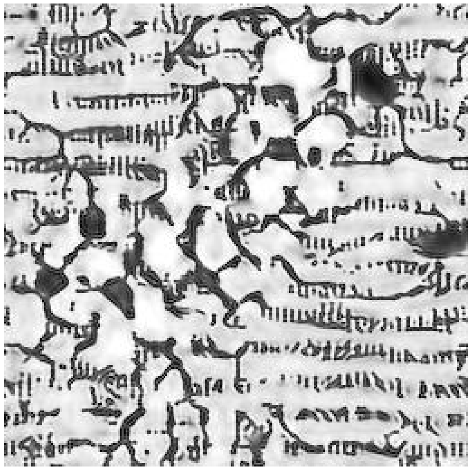
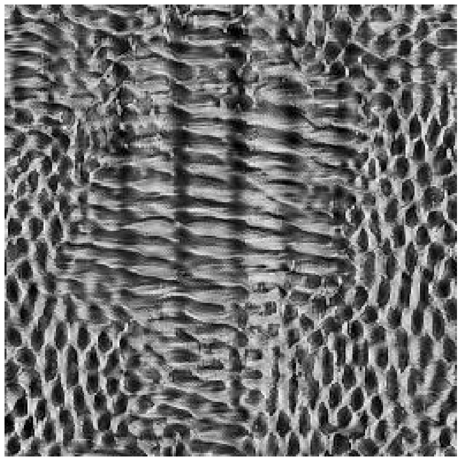


Modification: incorporate an additional projection operation in the synthesis loop, replacing central pixels by those of the original.

Scale Extrapolation

Modification: incorporate an additional projection operation in the synthesis loop, replacing coarse-resolution coefficients by those of the original.

Texture Mixtures


Modification: choose parameter vector that that is the average of those associated with two example textures.

Conclusions

- A framework for texture modeling, based on that originally proposed by Julesz
- New texture model:
  - based on biologically-inspired statistical measurements
  - includes methodology for testing
  - provides heuristic methodology for refinement
  - can be applied to a wide range of problems

Further information: `http://www.cns.nyu.edu/~lcv/texture`

To Do

- Adaptive front-end transformation (e.g., Zhu et al ’96, Manduchi & Portilla ’99)
- Eliminate redundancy of parameterization
- Applications: compression, super-resolution, texture interpolation, texture painting...