EECS 431
Human Perception and Electronic Media
Lecture 3

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Digital Halftoning

- Rendering continuous-tone images with printing/display devices that can directly represent only small number of output levels
- Desktop publishing
  - High quality printed material available to everyone
- Digital photography
  - Photographic quality images on inexpensive printers
- Printing industry
  - High volume offset printing vs. print-on-demand

Original Grayscale

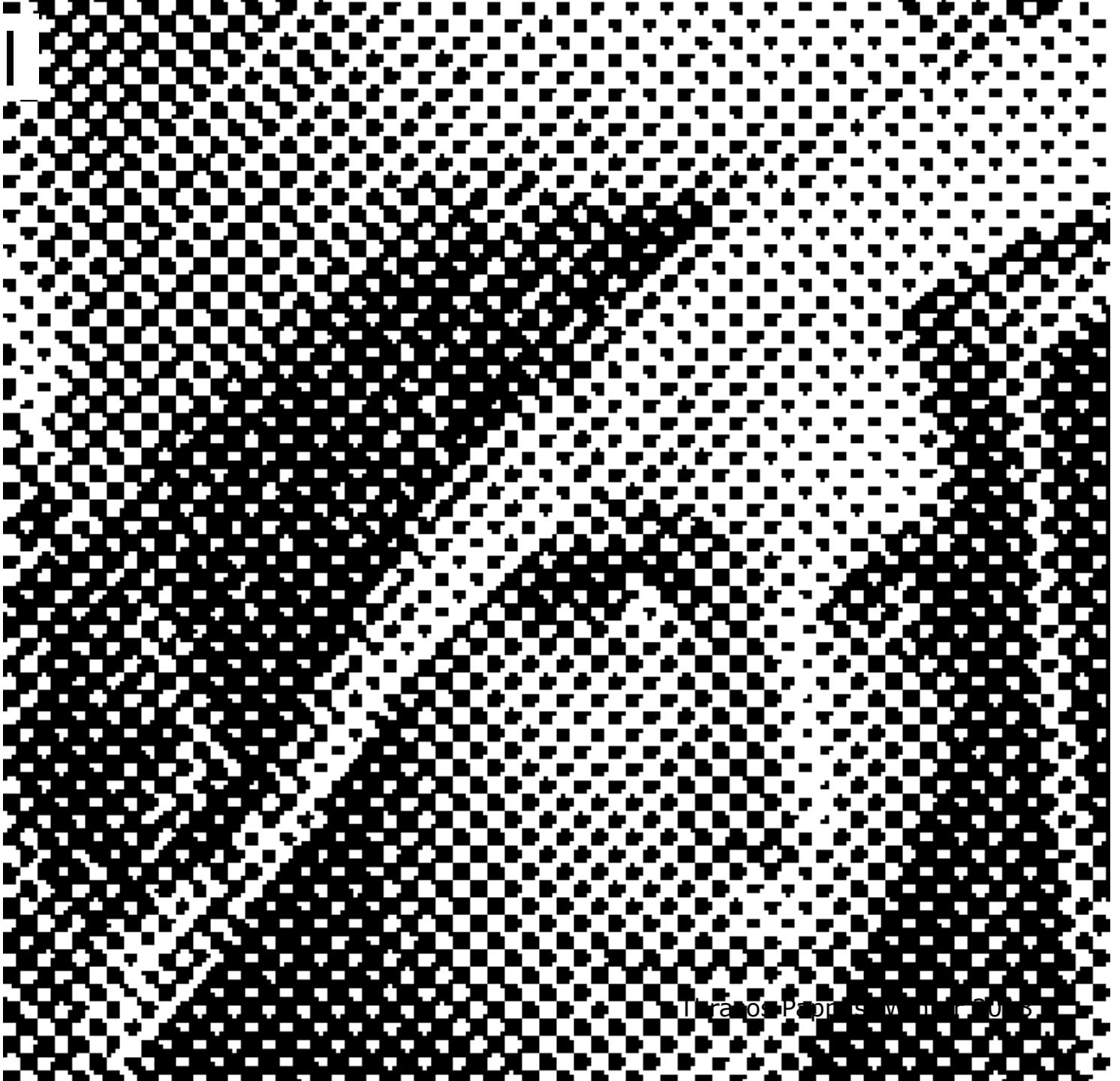
Threshold

Adaptive Threshold

Random

Line

Classical

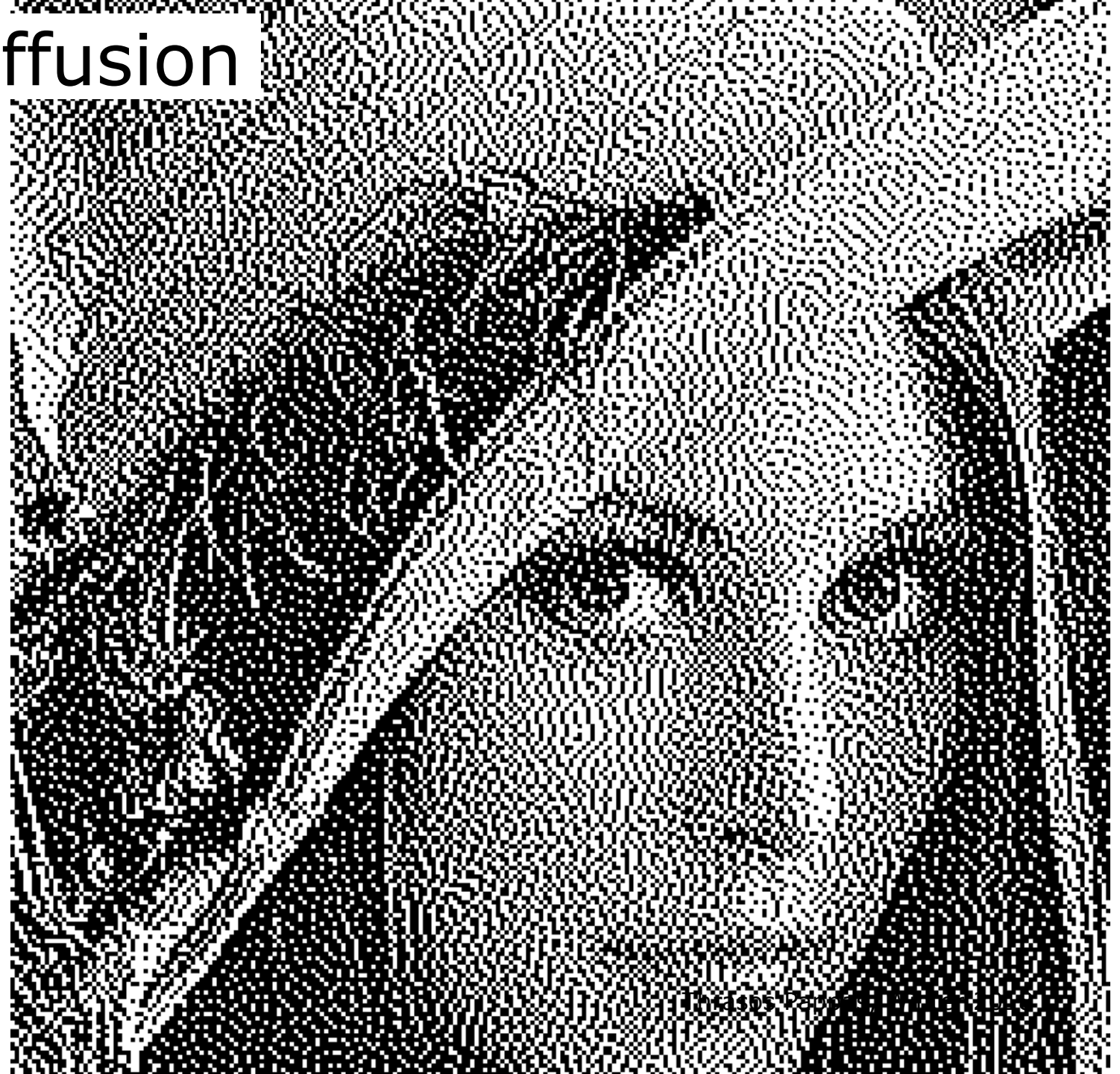


Bayer

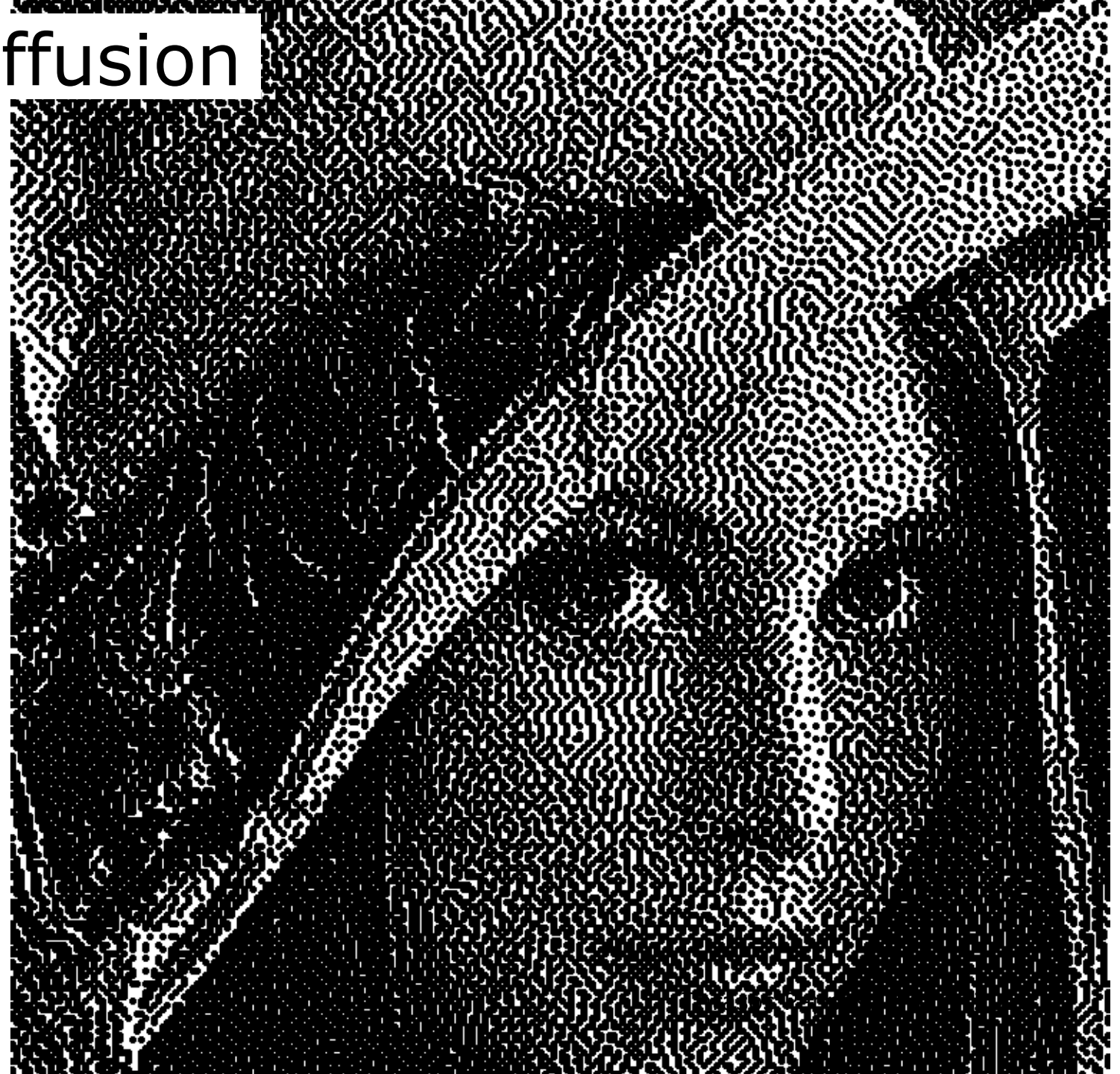
Blue Noise

Error Diffusion

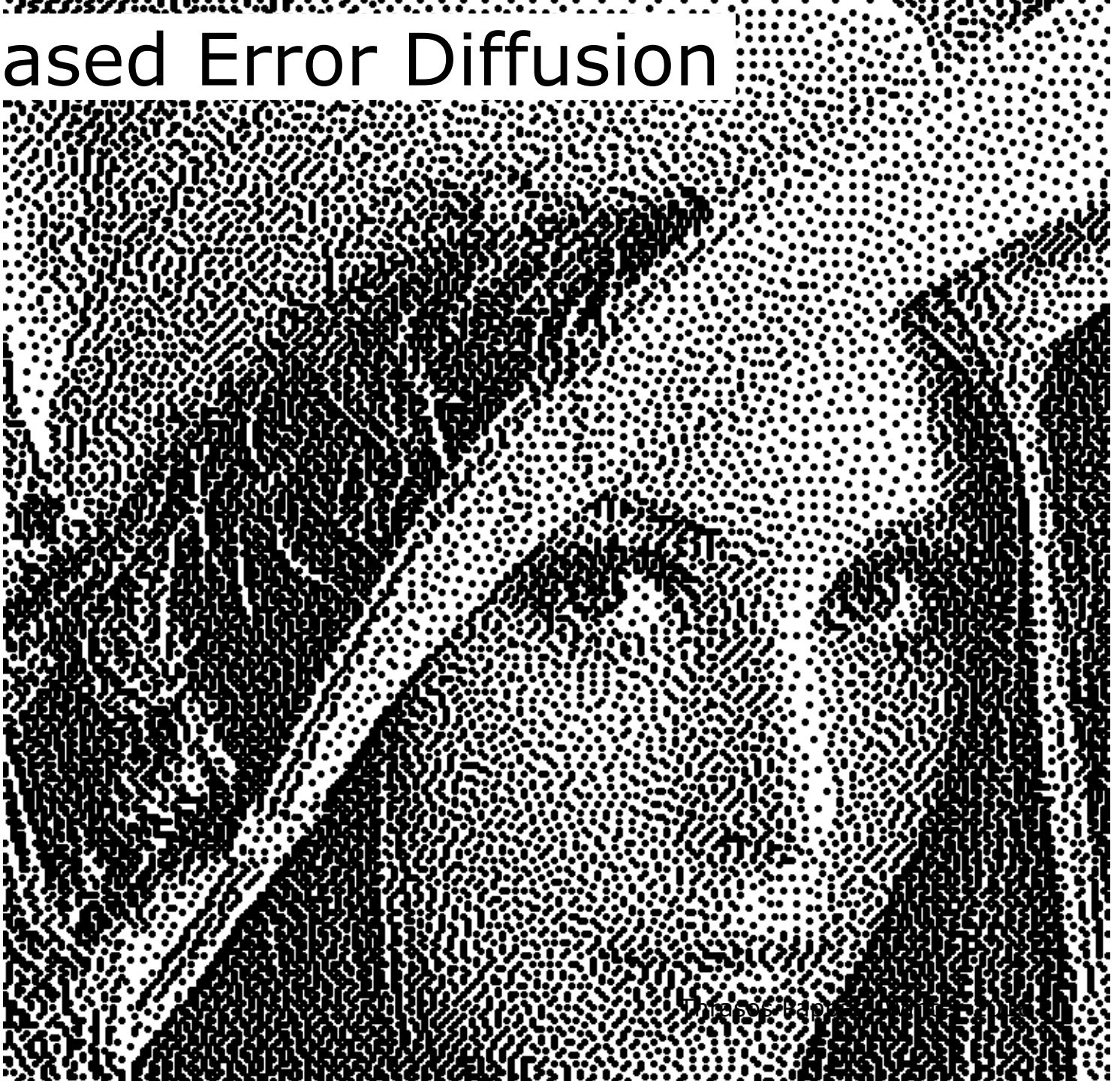
Error Diffusion



Error Diffusion



Model-Based Error Diffusion



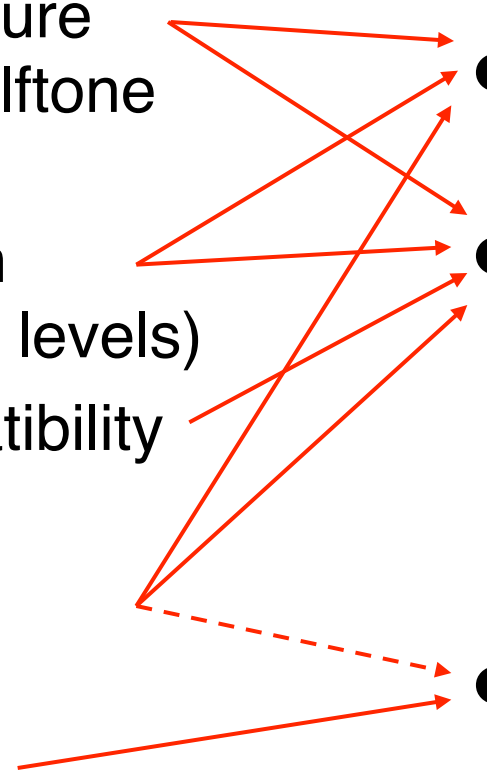
Halftoning Techniques

- Point algorithms
  - Screening (dithering)
- Neighborhood algorithms
  - Error diffusion
- Iterative algorithms
  - Least squares model-based (direct binary search)

- All can incorporate HVS and printer models

Halftone Quality

- Halftone-induced texture (visibility/quality of halftone patterns)
- Tone-scale resolution (number of perceived levels)
- Adjacent level compatibility (of halftone textures)
- Tone-scale accuracy (display device)
- Spatial resolution (sharpness)

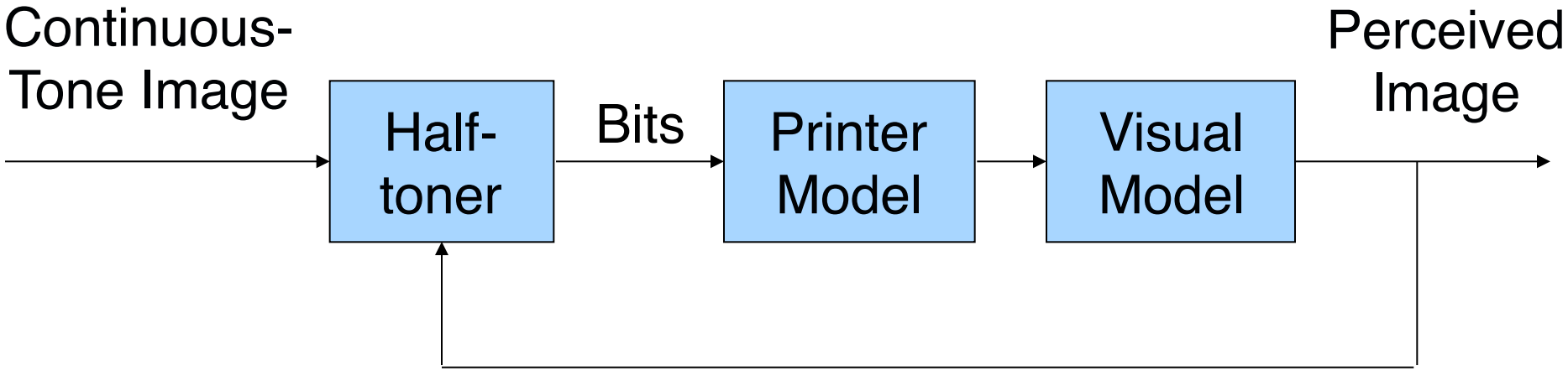


- Constant tone-level
- Slowly changing tone-level (smooth regions)
- Rapidly changing tone-level (edges)

Halftone Quality Tradeoffs

- Traditional halftoning techniques (clustered-dot screens)
  - Spatial resolution and texture vs. Tone-scale resolution and accuracy
- Error diffusion and iterative techniques
  - Texture vs. tone-scale resolution
  - Spatial resolution is very high
- Other tradeoffs
  - Robustness to printer distortions (clustered-dot) vs. better spatial resolution and texture (model-based error diffusion and iterative techniques)
  - Green-noise halftoning

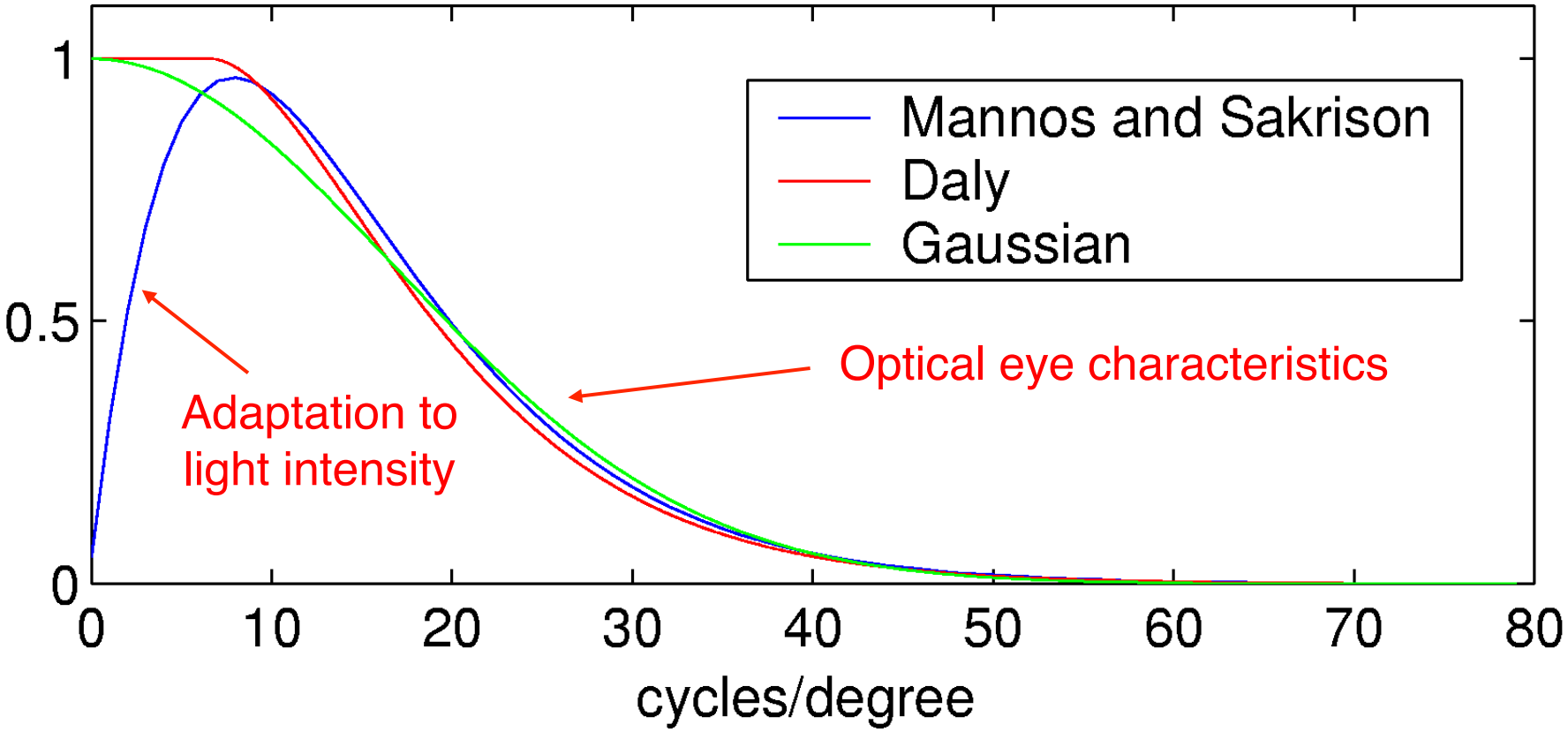
Model-Based Halftoning



HVS Models

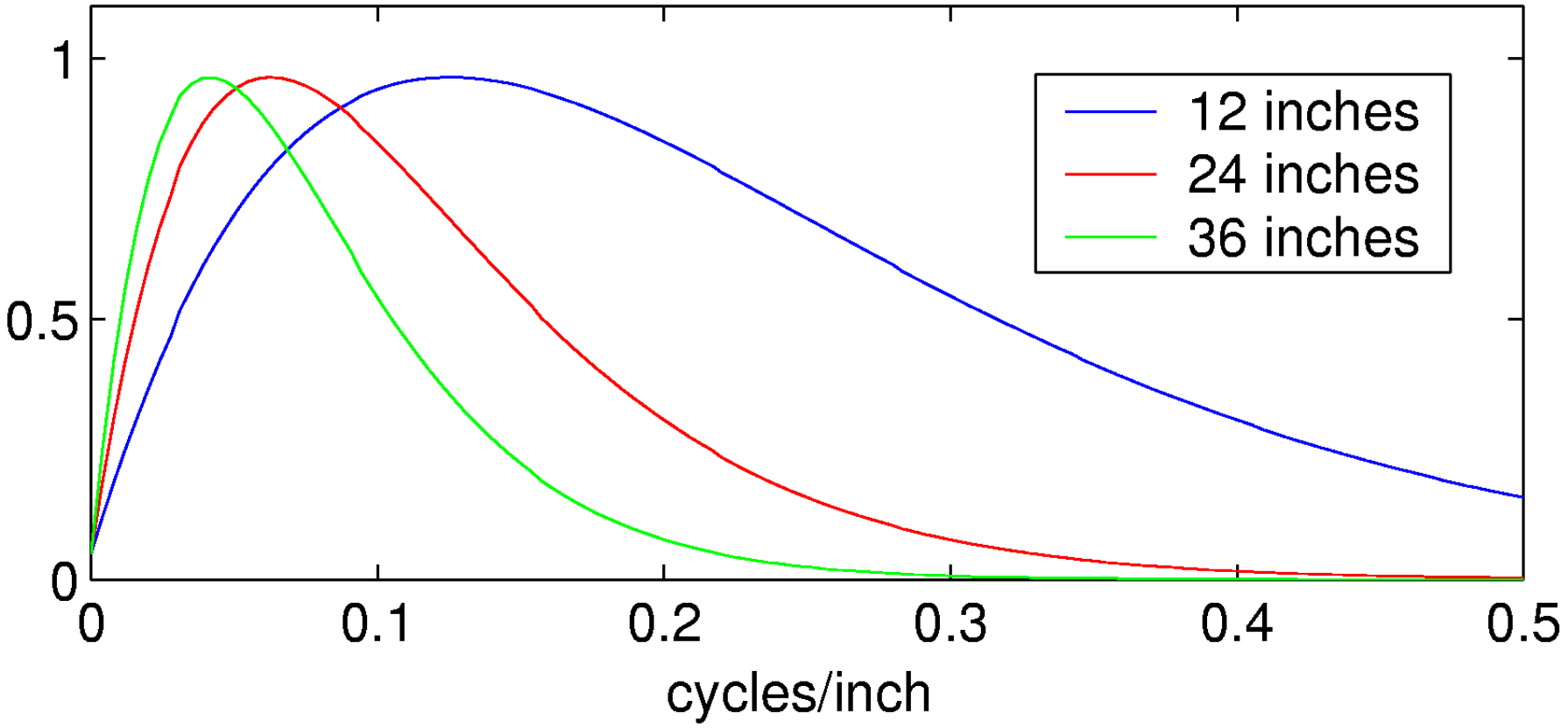
- All halftoning algorithms rely on the fact that the eye acts as a spatial low-pass filter
- Vision-based algorithms use explicit models of the HVS to produce halftones of higher visual quality
- HVS models vs. visual fidelity metrics
  - Single filter-based models (simple computation)
  - Multichannel models (image quality/compression)

HVS Models



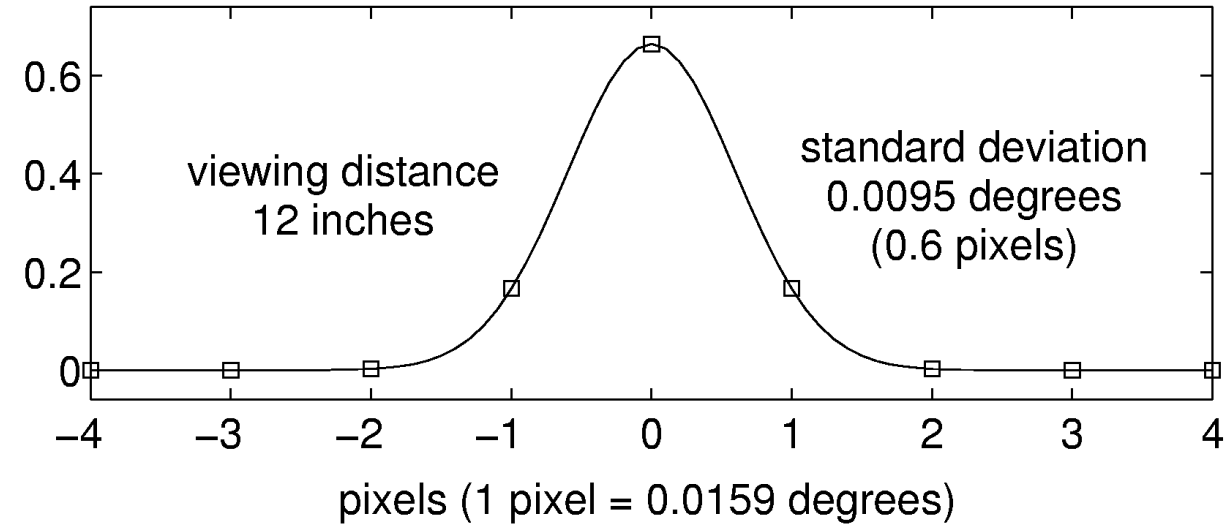
- Viewers cannot be expected to maintain fixed distance
- Eye is less sensitive to diagonal features

HVS Models

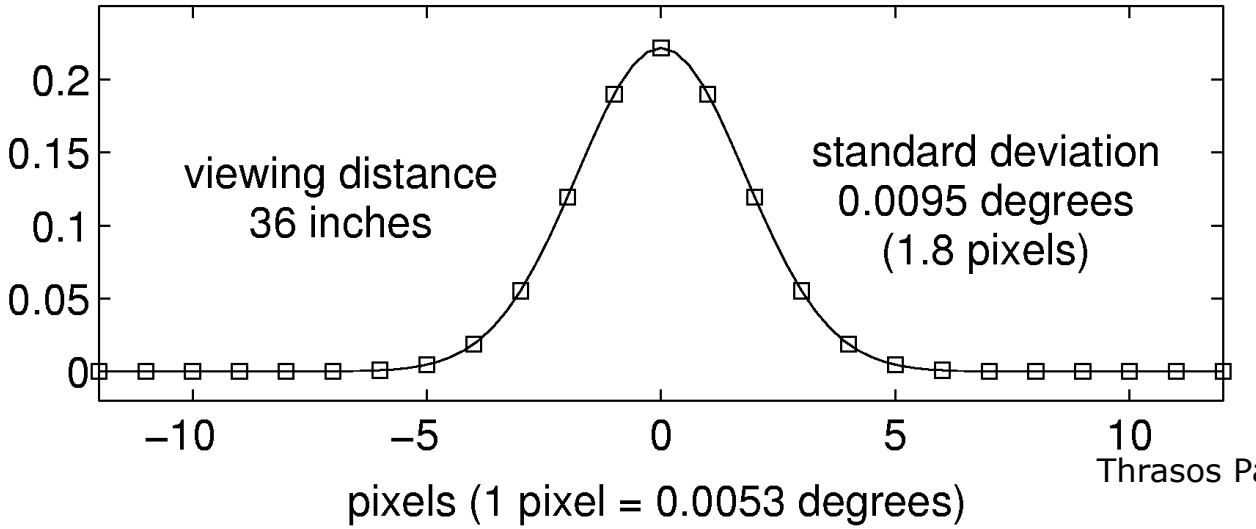


- Viewing distance
- Printer resolution

HVS Models



300 dpi



HVS Models

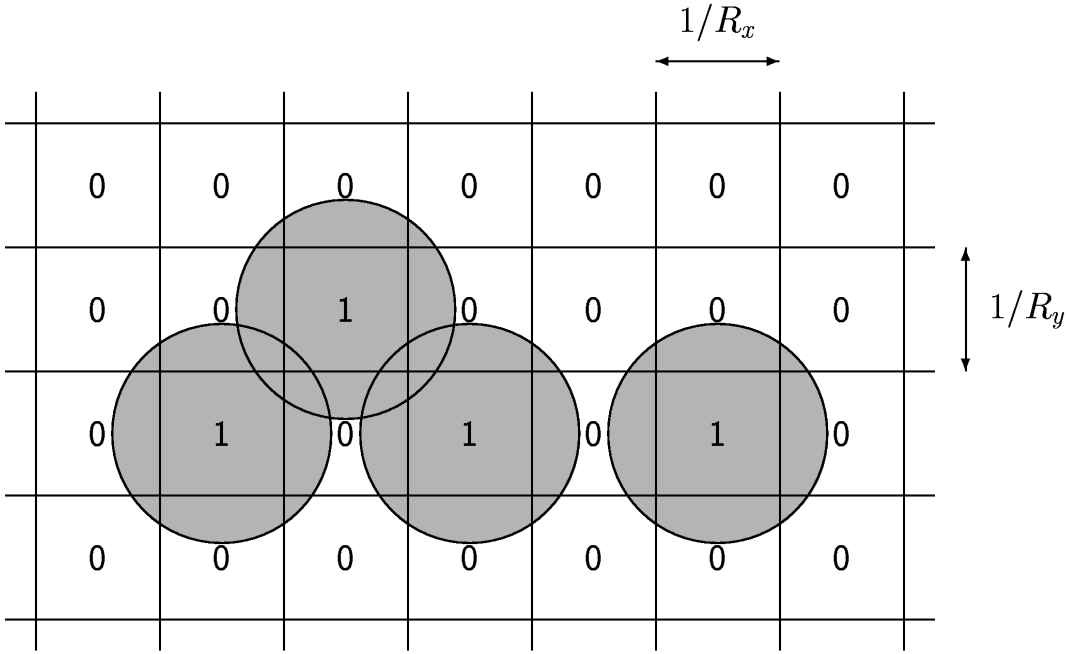
- Scale factor s
  - s = viewing distance X printer resolution
  - Perceived resolution in dots per radian
  - Tradeoff between texture and tone-scale resolution
- Small s: Dots are visible
  - Fine textures
  - Few gray levels - Few patterns to chose from
- Large s: Eye averages several pixels
  - Coarse halftone patterns acceptable
  - Many gray levels - Many pattern choices

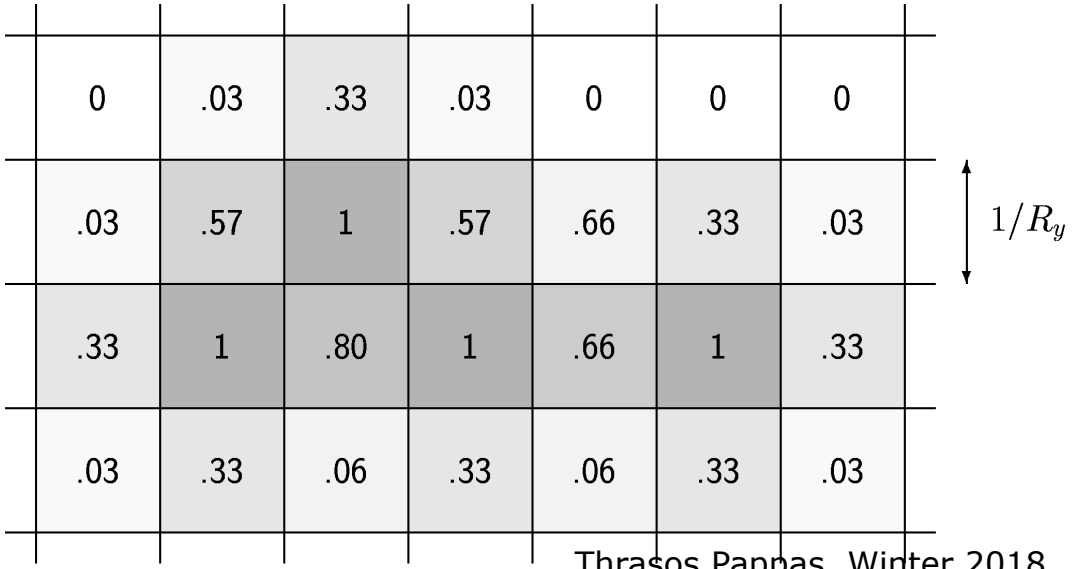
Printer Models

- B&W and color printers
  - Electrophotographic, inkjet
- Printer effects
  - Dot overlap
  - Mechanical, optical, electric field dot gain
  - Other nonlinearities

- Predict gray levels produced by printer
- Easy to incorporate in halftoning algorithm

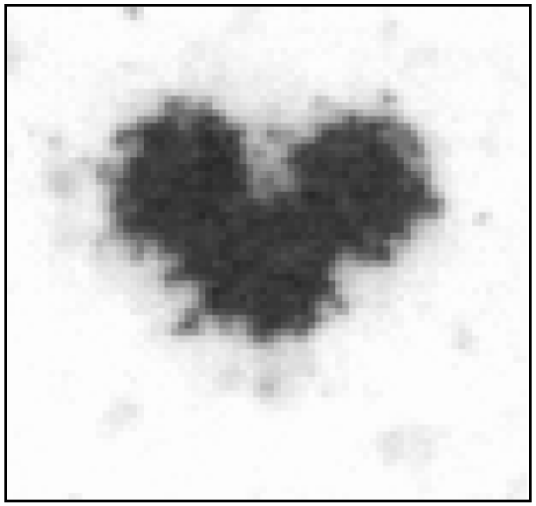
Printer Models



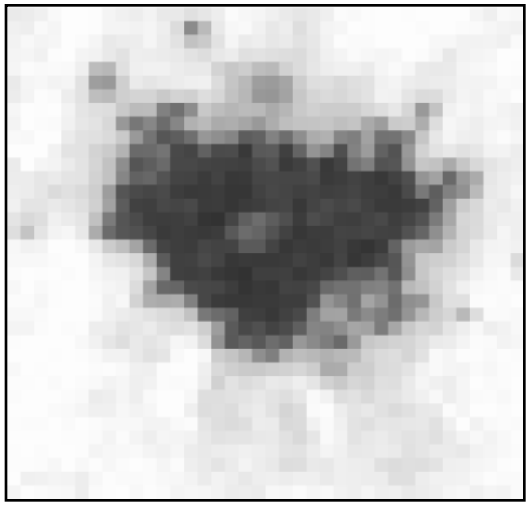


Sampled grayscale printer model

Printer Models



0	0	0	0	0
0	1	0	1	0
0	0	1	0	0
0	0	0	0	0



300 dpi

Halftone pattern

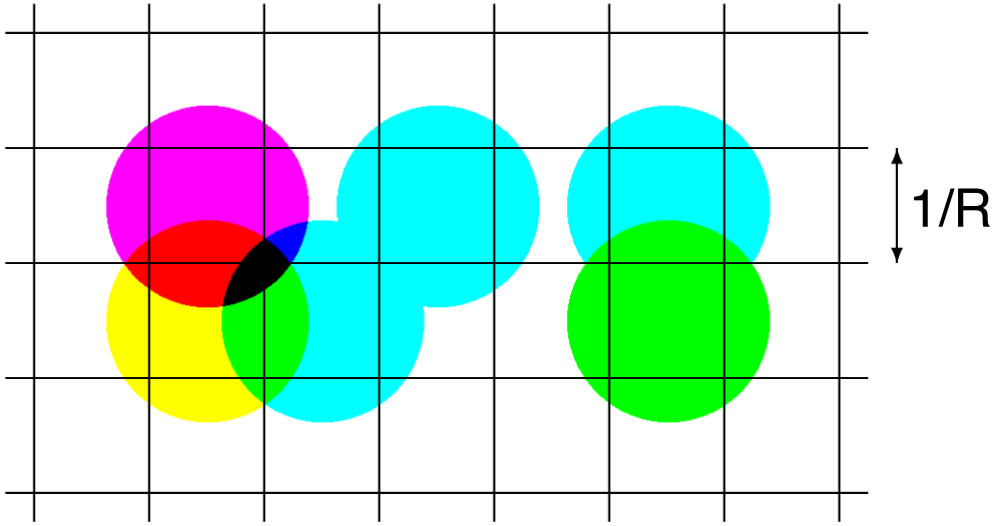
600 dpi

* Figure provided by Jan Allebach

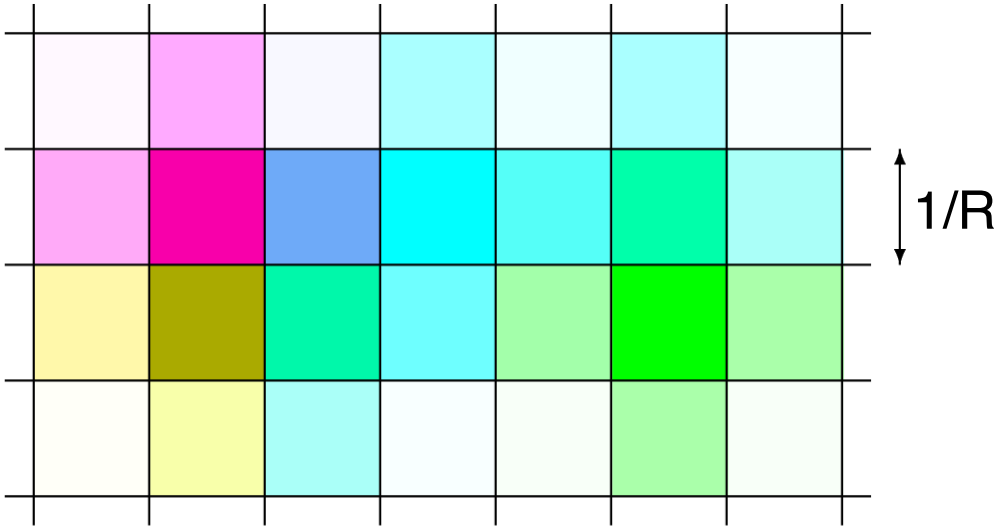
Printer Models

- Circular black dots
  - First order approximation
  - Dot size, shape, placement, density of colorant may vary
- Sampled grayscale printer model
  - Deterministic or probabilistic
  - Can be specified as a table
  - Can be derived from physical considerations or can be based on measurements (macroscopic or microscopic)

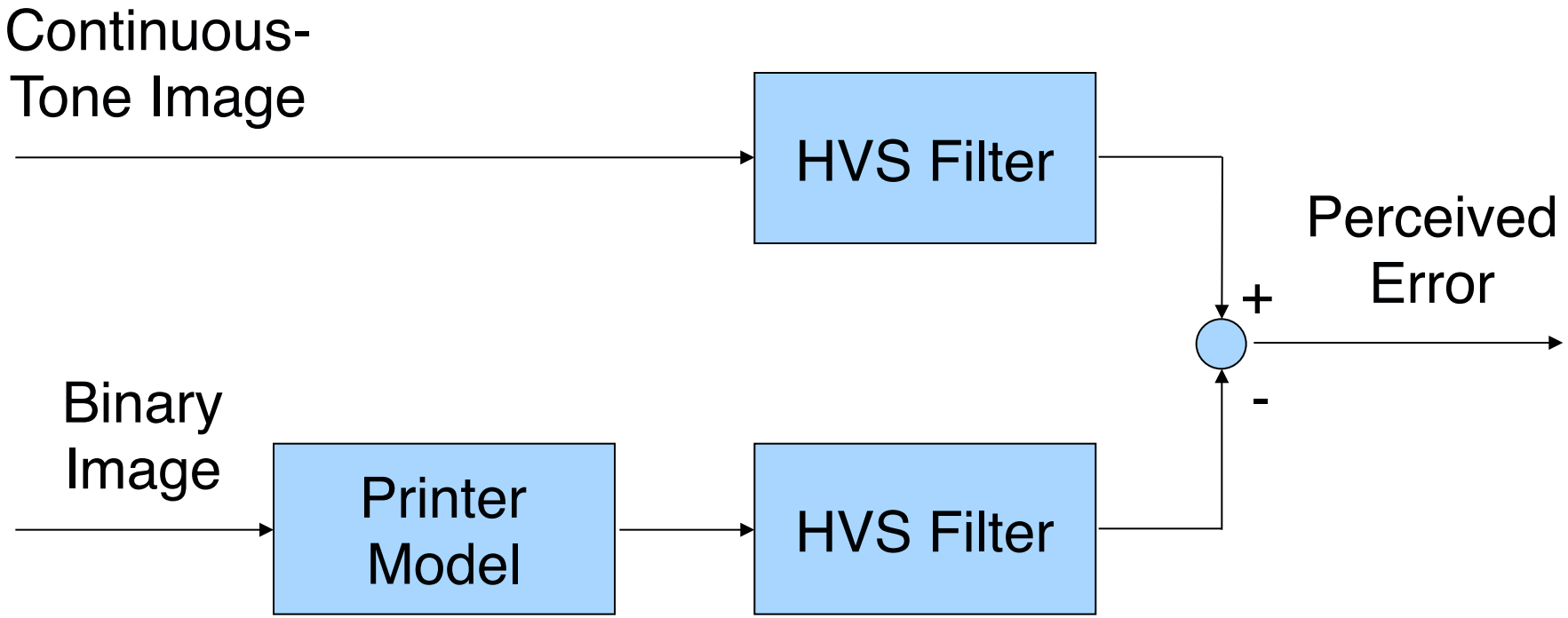
Color Printer Models



Sampled tonescale printer model



Least-Squares Model-Based Halftoning

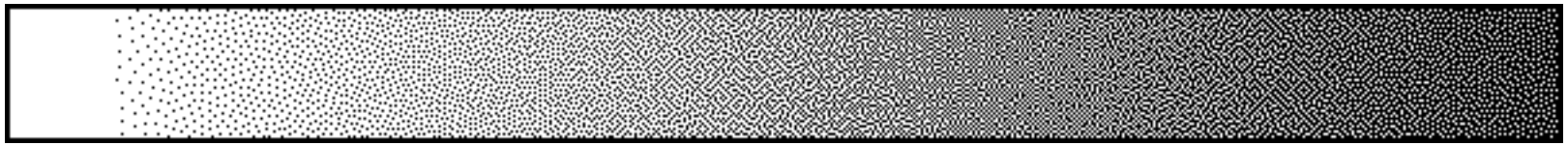


- Binary image that minimizes square of perceived error

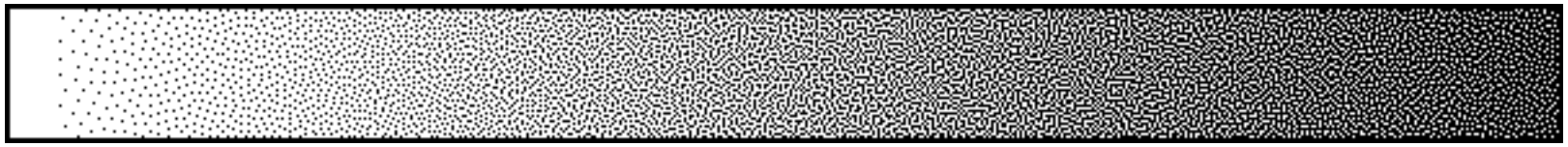
Least-Squares Model-Based Halftoning

- Exhaustive search: 2^N patterns (10^{77} for 16x16 image)
- Iterative techniques that produce local optima
- Depending on optimization strategy, visual quality may depend on starting point
- Toggle/swap scheme proposed by Allebach produces excellent results, independent of starting point
- Simulated annealing techniques offer no significant improvements in image quality
- Viewing distance/printer resolution (scale factor s) affect
  - Coarseness of halftone textures and number of perceived graylevels (at appropriate viewing distance)
  - Number of iterations for convergence

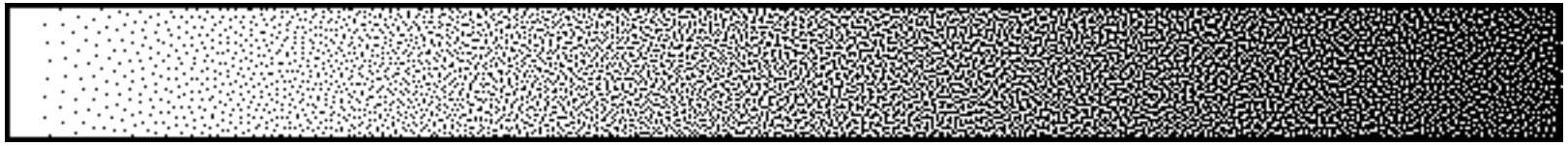
Least-Squares Model-Based Halftoning



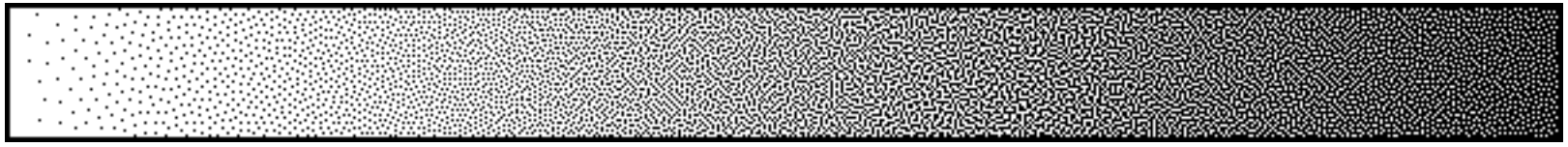
LSMB/DBS, 300 dpi, 0.5 ft



LSMB/DBS, 300 dpi, 1 ft



LSMB/DBS, 300 dpi, 2 ft

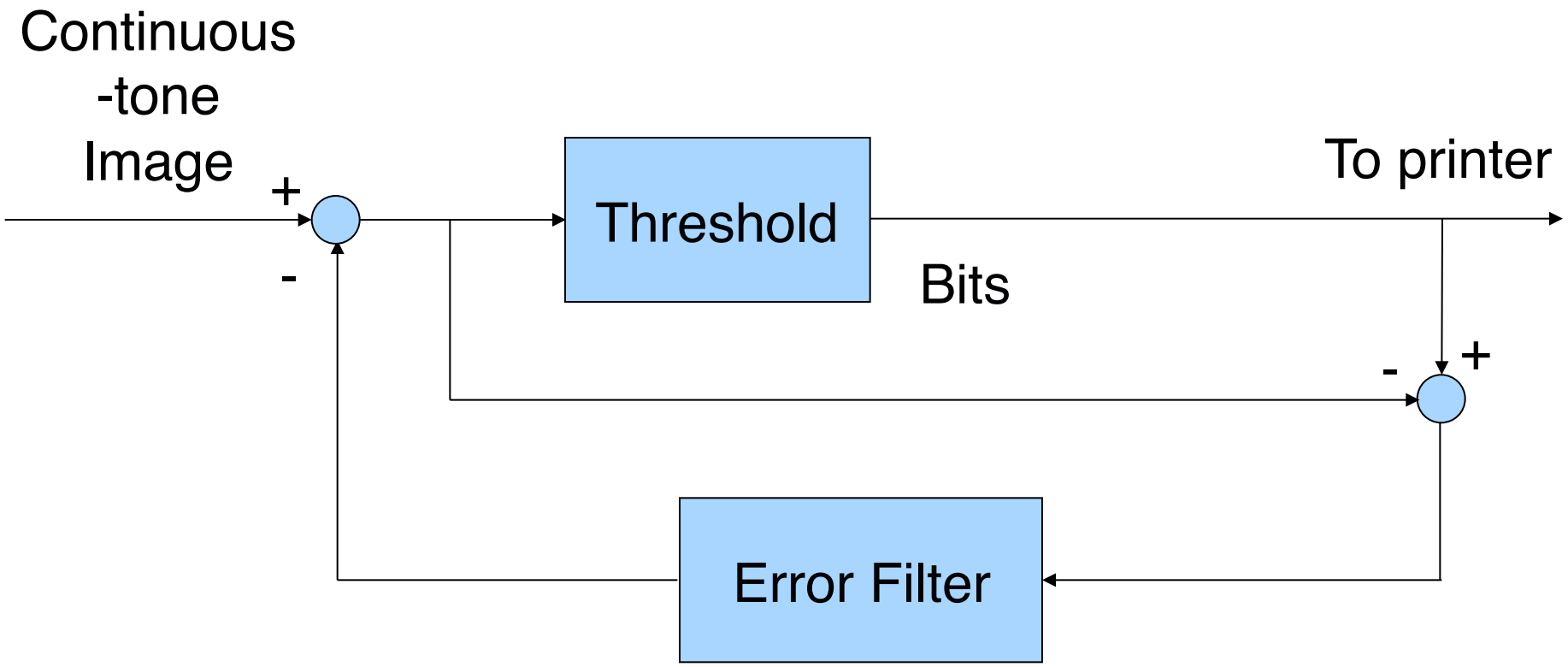


Dual-metric DBS (Kim, Allebach' 02)

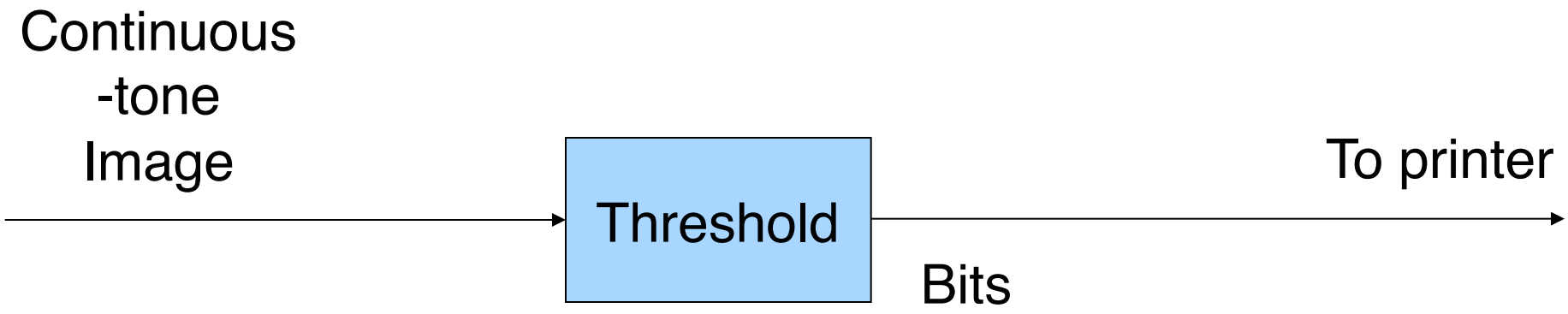
HVS Models

- Scale factor s provides tradeoff between texture and tone-scale resolution
  - Even when viewing distance and printer resolution is known
  - Dual metric approach for LSMB/DBS algorithm (Kim & Allebach’02): large s in highlights, shadows, and midtones; small s everywhere else

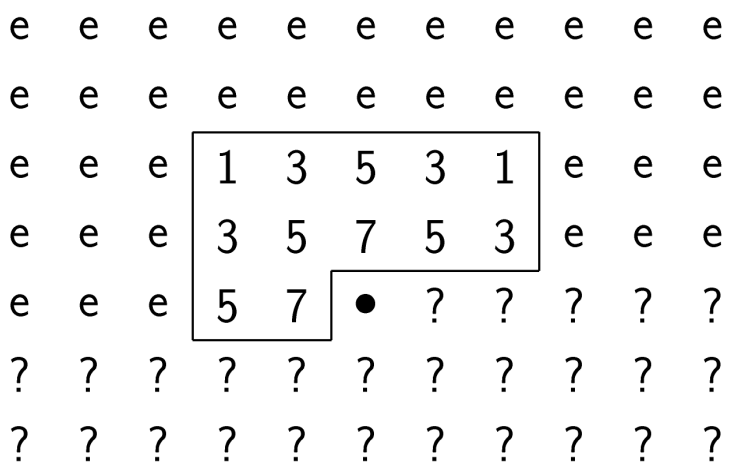
Error Diffusion



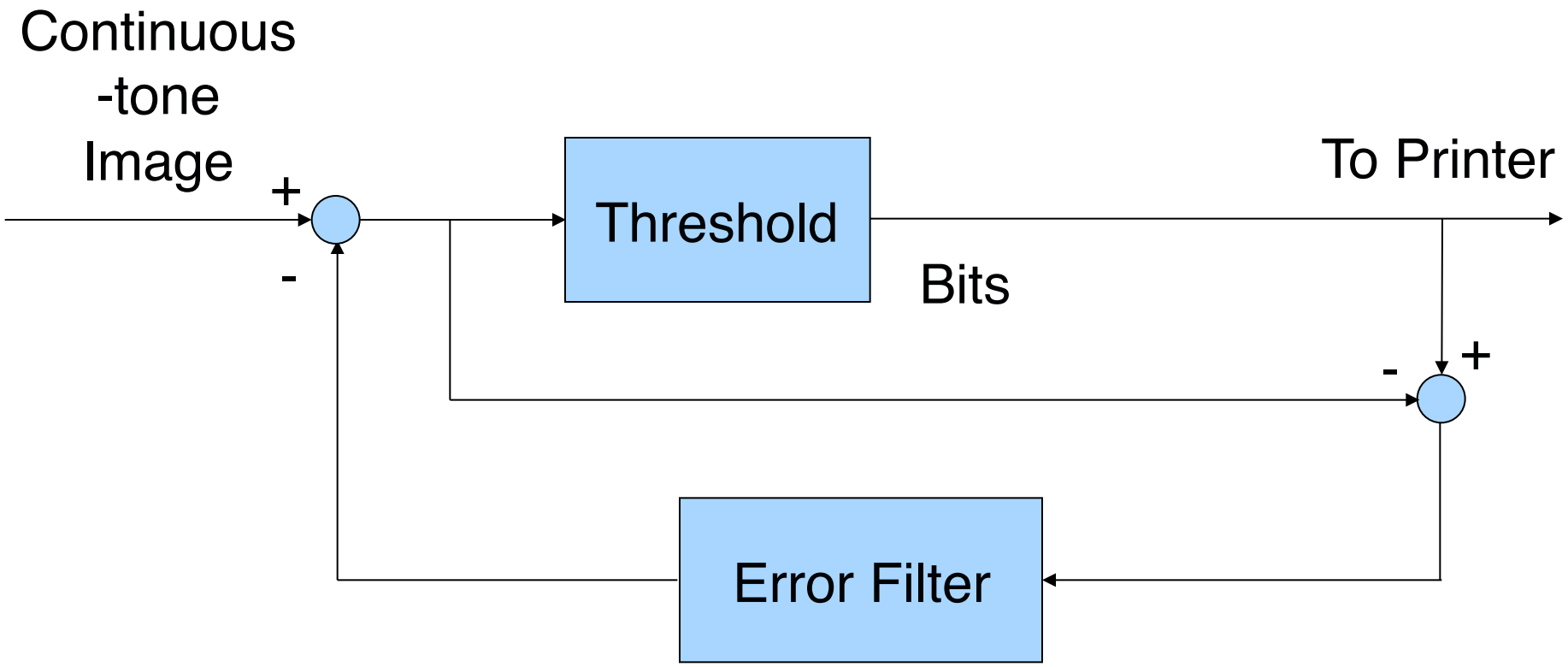
Error Diffusion



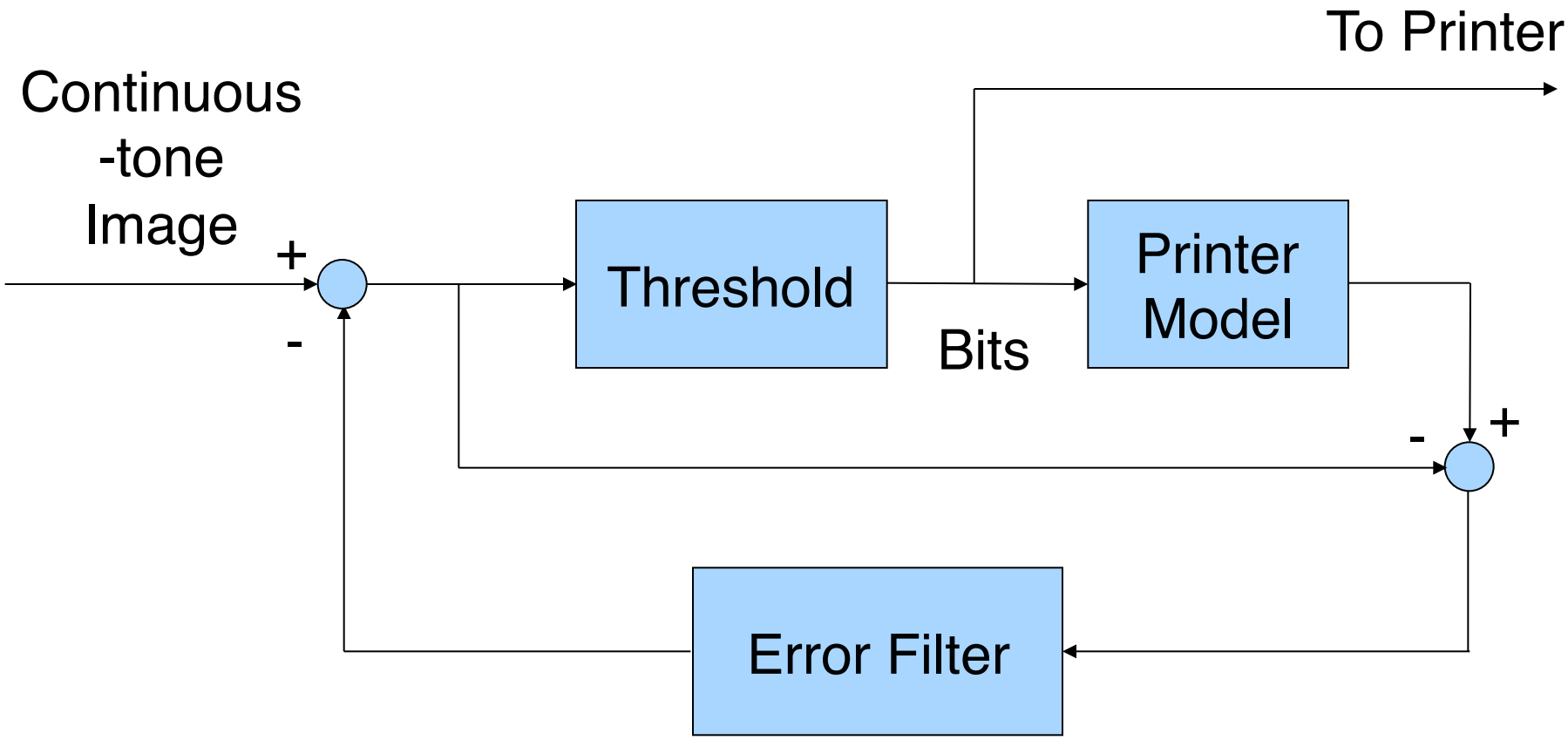
Error Diffusion Filter



Error Diffusion

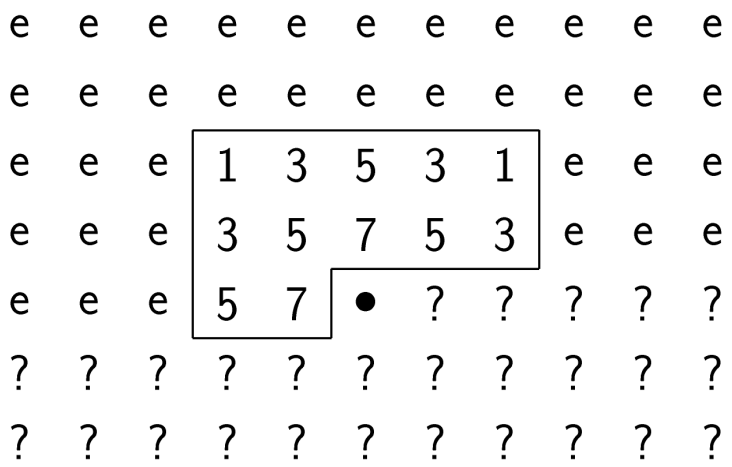


Model-Based Error Diffusion

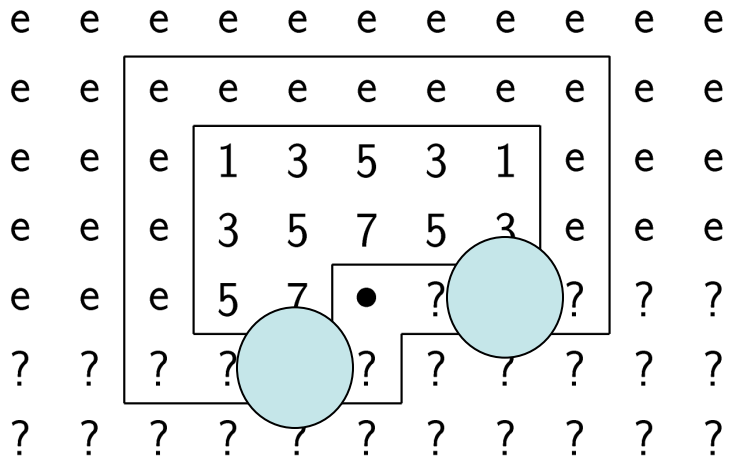


Multi-pass Model-Based Error Diffusion

Standard ED



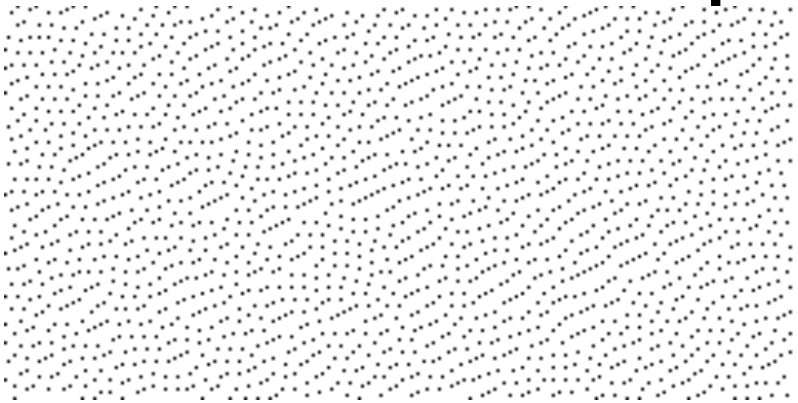
Model-based ED

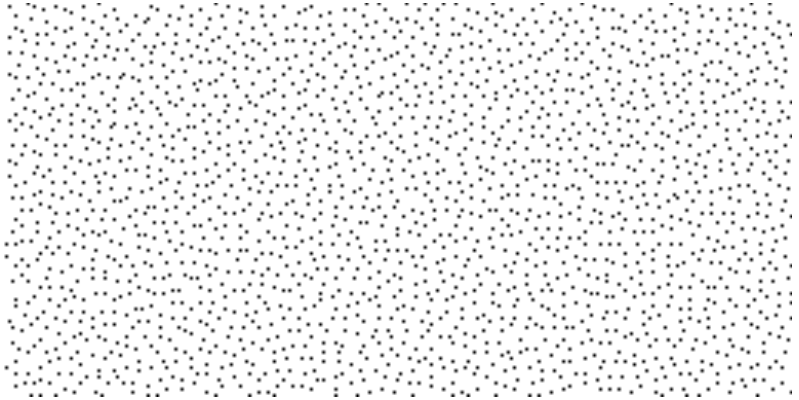


Error Diffusion Modifications

- Threshold and weight perturbations (Ulichney' 87)
- Space filling curves (Witten & Neal' 82, Vehlo & Gomes' 91)
- Dot diffusion (Knuth' 87)
- "Optimized" error diffusion (Kolpatzik & Bouman' 92)
- More symmetric error distribution (Fan' 94)
- Modified error diffusion weights (Fan' 93, Shiau & Fan' 96)
- Edge enhancement using input-dependent threshold (Eschbach & Knox' 91)
- NL detail enhancement (Thurnhofer & Mitra' 94)
- Adaptive threshold modulation (Damera-Venkata & Evans' 01)

Halftone Quality/Visibility & Radial Spectra



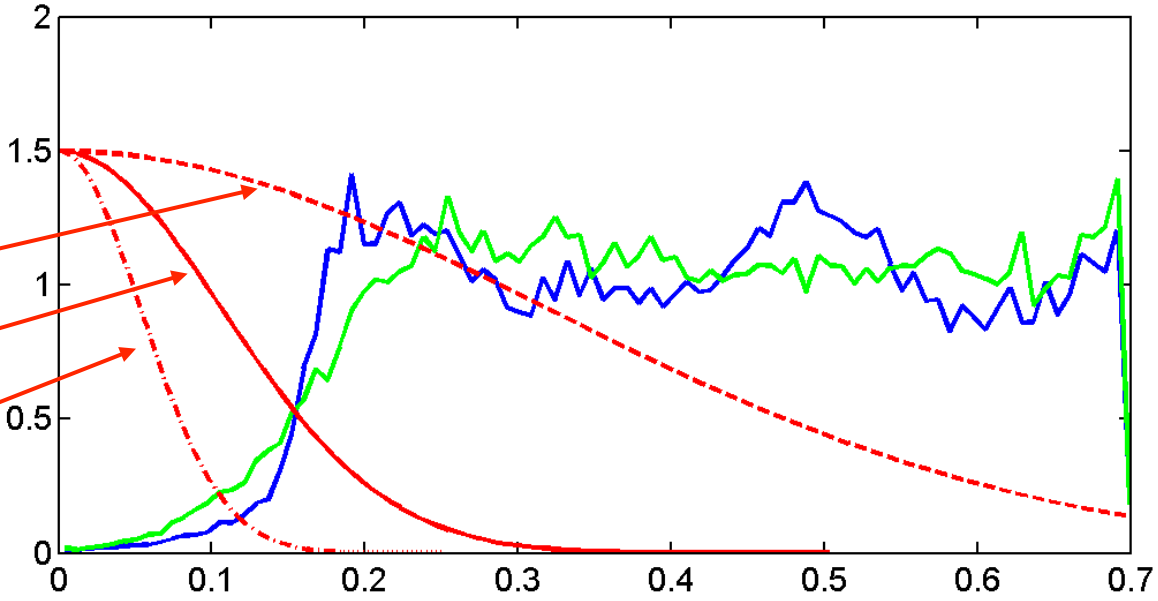


at 30 inches

100 dpi

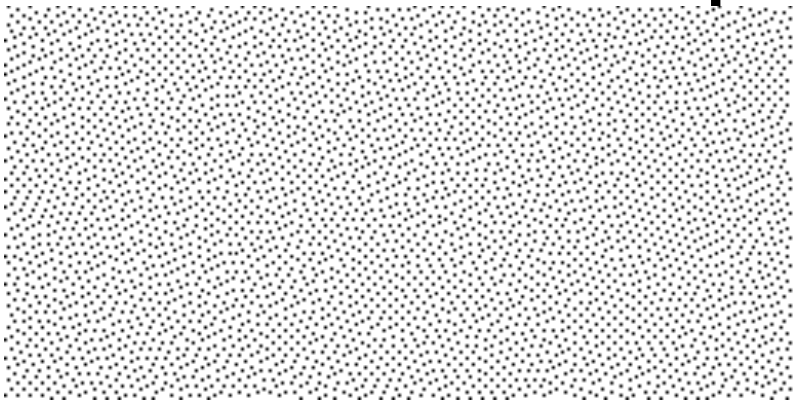
300 dpi

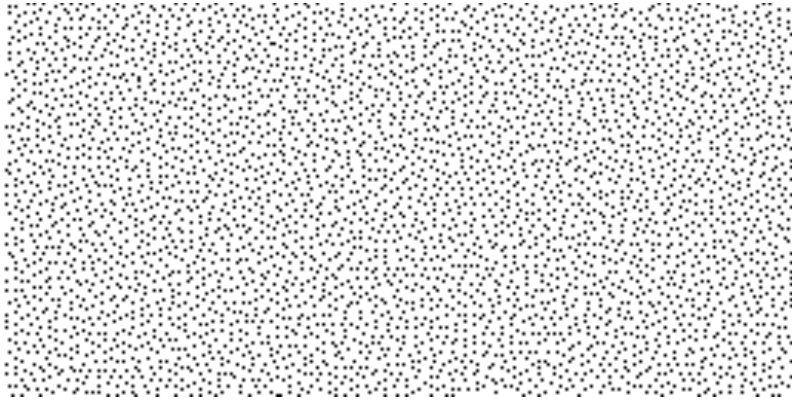
600 dpi



(radial frequency)/(printer resolution in dots per degree)

Halftone Quality/Visibility & Radial Spectra





at 30 inches

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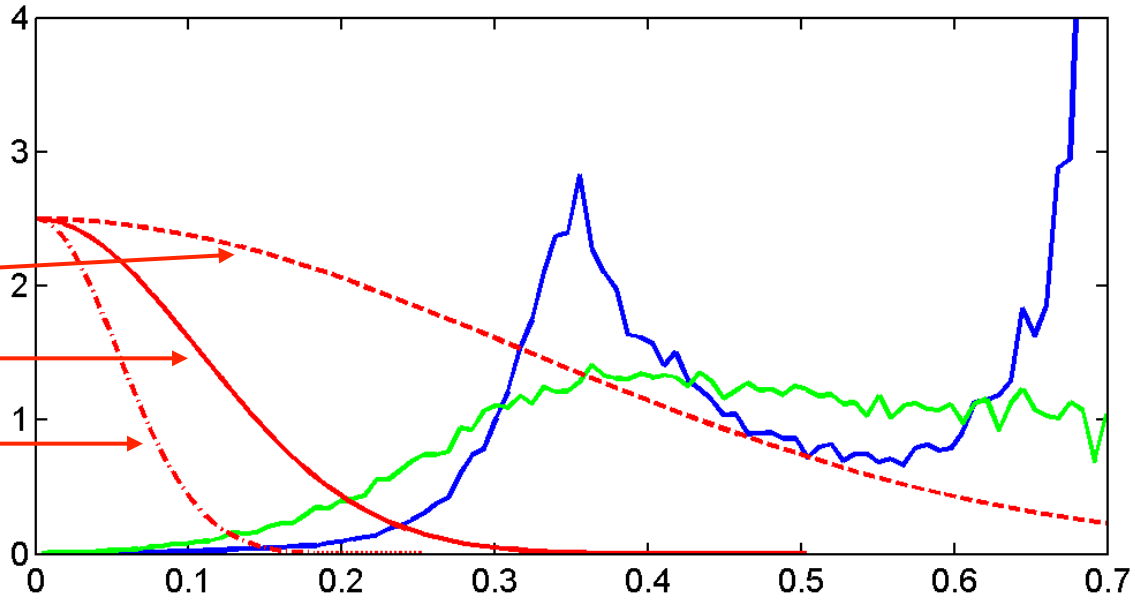
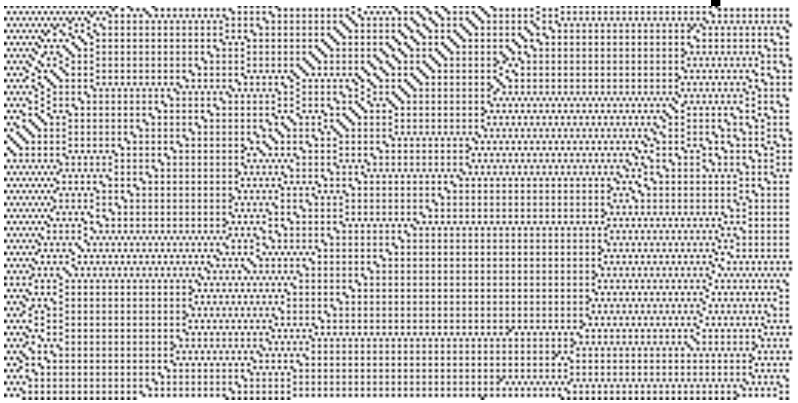
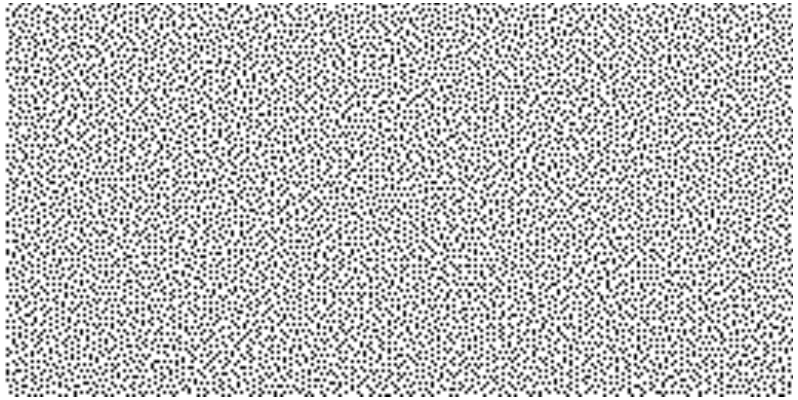


(radial frequency)/(printer resolution in dots per degree)

Halftone Quality/Visibility & Radial Spectra





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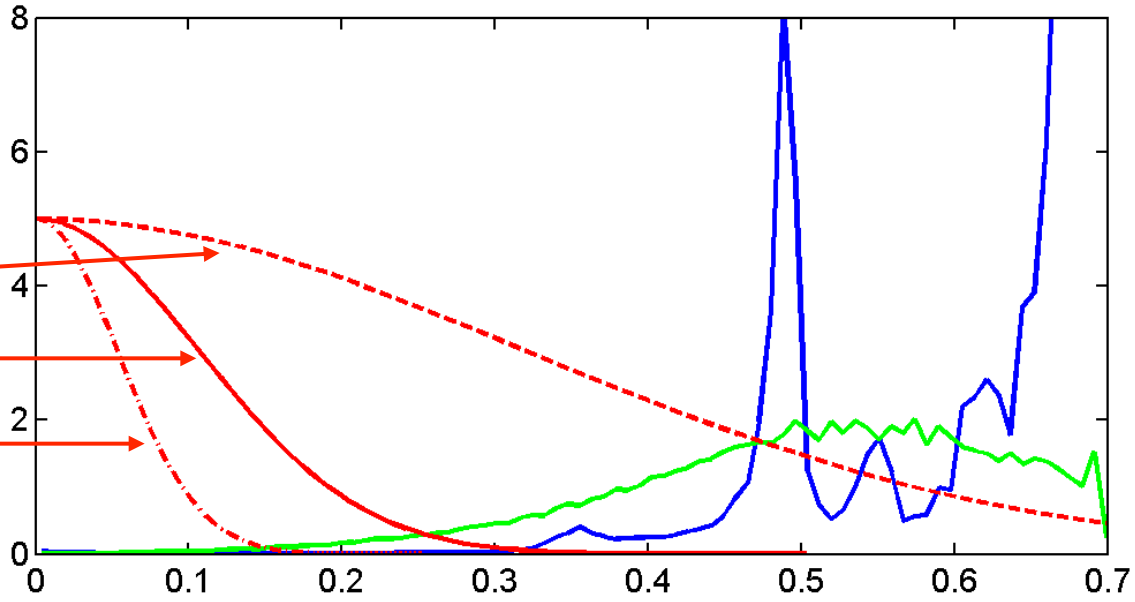

(radial frequency)/(printer resolution in dots per degree)

Green-Noise Halftoning

- Generate visually pleasing ED-type patterns with various degrees of clustering
  - Error diffusion with output-dependent feedback (Levien’92)
  - Green-noise halftoning (Lau, Arce, Gallagher’98)

Tone-Dependent Error Diffusion

- Varying the weights as a function of graylevel (Eschbach’93, Shu’95, Ostromoukhov’01)
- Tone-dependent weights, serpentine raster, two tone-dependent thresholds (Li & Allebach’02)
  - Optimized parameters using HVS-based cost function

Blue-Noise Screening

- Attempts to simulate error diffusion
  - Power-spectrum matching (Mitsa & Parker' 91)
  - "Void-and-cluster" (Ulichney' 93)
  - Gaussian filter used to find largest void and tightest cluster can be interpreted as HVS point spread function
- Can account for printer distortions
- Green-noise screening
  - (Lau, Arce, Gallagher' 99)

Image Halftoning

- T. N. Pappas, J. P. Allebach, and D. L. Neuhoff, “Model-based digital halftoning,” *IEEE Signal Processing Mag.,* vol. 20, pp. 14-27, July 2003.