Model-Based Halftoning

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ICIP-2004, October 26, 2004

Acknowledgements

David Neuhoff, University of Michigan

Jan Allebach, Purdue University

Digital Halftoning

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

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

Examples (VGs)

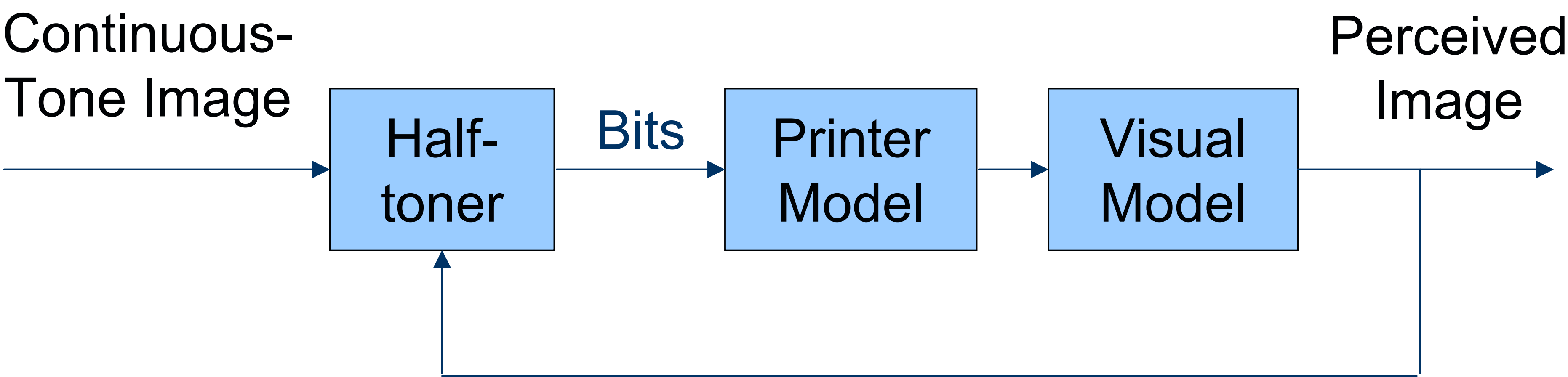
Halftoning Computation

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

- All can incorporate models (HVS or printer)

Examples (VGs)

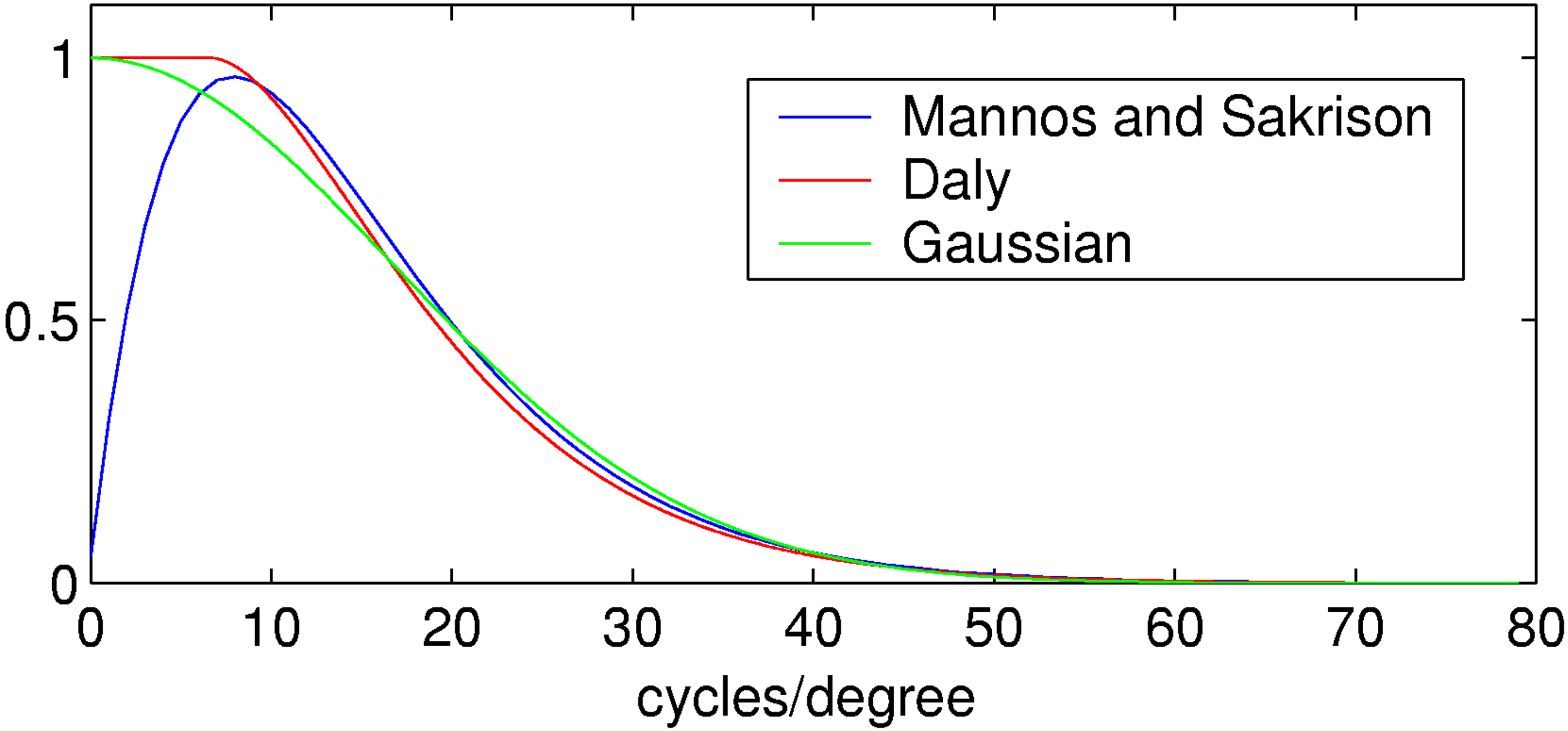
Model-Based Halftoning



HVS Models

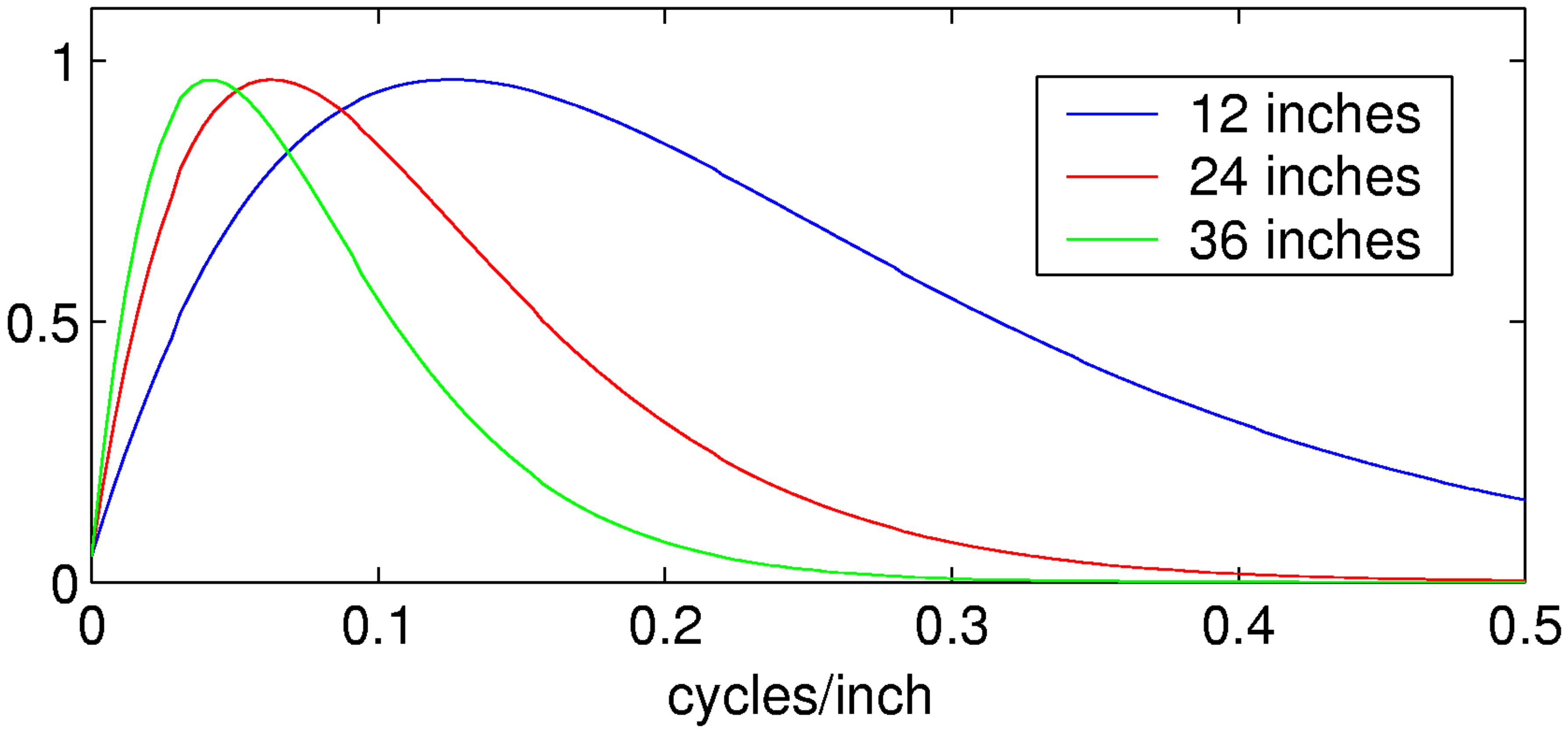
- All halftoning algorithms rely on the fact that the eye acts as a spatial low-pass filter
- Vision-based algorithms use explicit models of the HVS to produce halftones of higher visual quality
- HVS models vs. visual fidelity metrics
- Multichannel models
  - Perceptual metrics for image quality/compression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

Eye Models



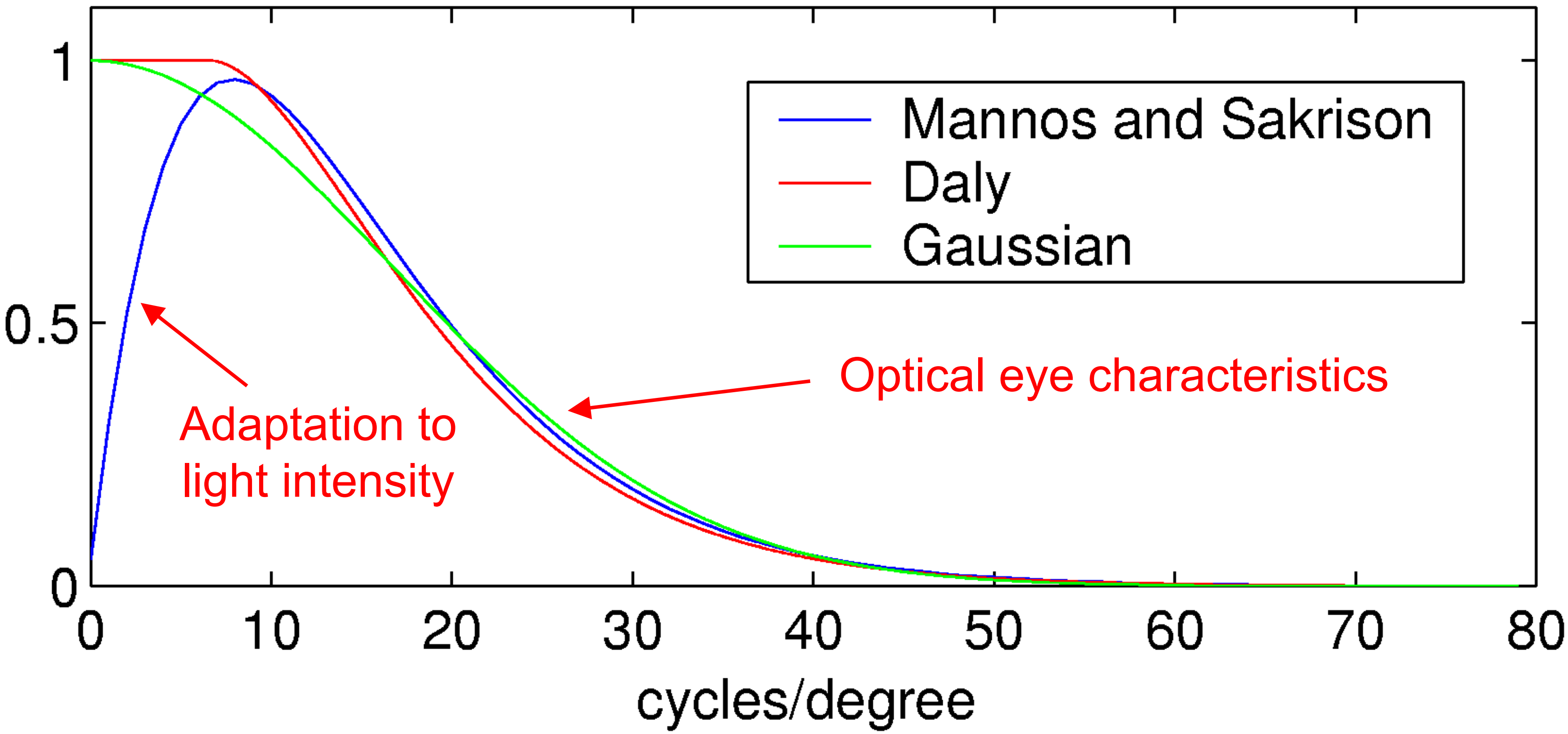
- Eye is less sensitive to diagonal features

Eye Models



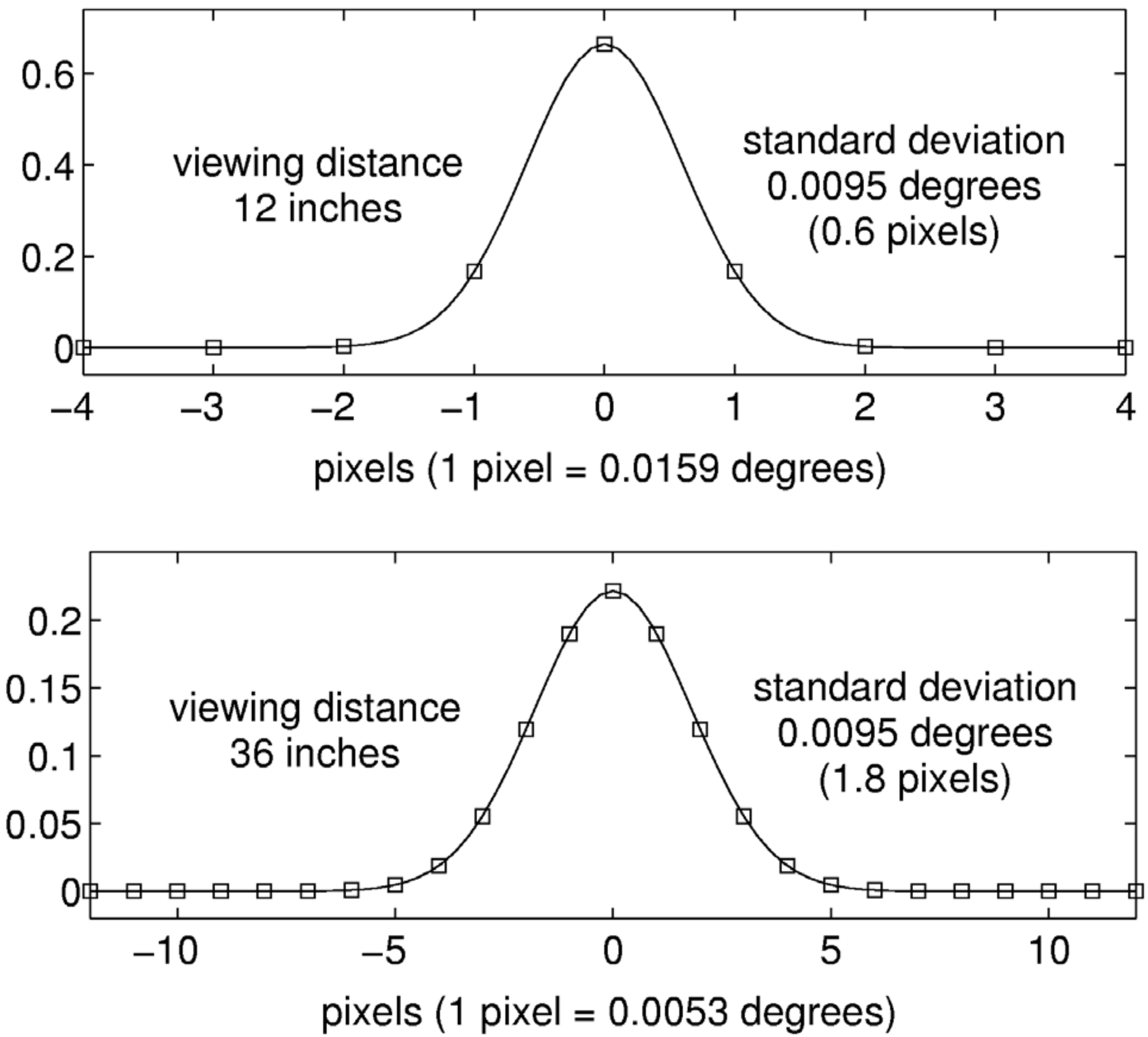
- Viewing distance
- Printer resolution

Eye Models



- Viewers cannot be expected to maintain fixed distance

Eye Models



300 dpi

HVS Models

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

HVS Models

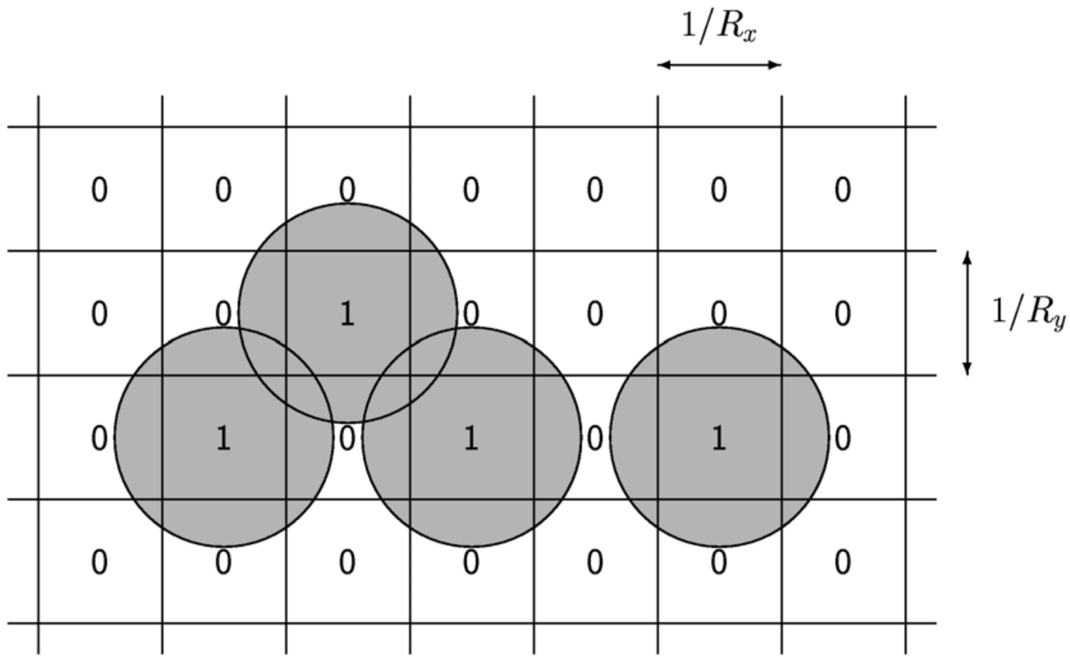
- Scale factor s provides tradeoff between texture and tone-scale resolution
  - Even when viewing distance and printer resolution is known
  - Dual metric approach for LSMB/DBS algorithm (Kim & Allebach 02): large s in highlights, shadows, and midtones; small s everywhere else

Printer Models

- B&W and color printers
  - Electrophotographic, inkjet
- Other display devices
- 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

0	.03	.33	.03	0	0	0
.03	.57	1	.57	.66	.33	.03
.33	1	.80	1	.66	1	.33
.03	.33	.06	.33	.06	.33	.03

$1/R_y$

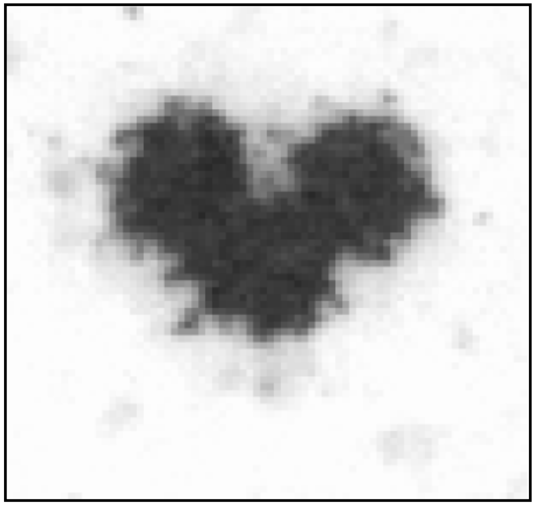
Printer Models

- Circular black dots: First order approximation only
- Dot size, shape, density of colorant (absorption), placement may vary
- Dot modulation capabilities
  - Each pixel can be in several hundred states
  - Assume binary printers (B&W and color)
- Sampled grayscale printer model estimates average level for each pixel as a function $\mathbb{P}$ of the binary specification of the surrounding pixels
- $\mathbb{P}$ can be deterministic or probabilistic
- $\mathbb{P}$ can be derived from physical considerations or can be based on measurements

Tabular Printer Models

- Specify $\mathbb{P}$ as table that lists graylevel for each binary pattern
- Dot interactions too complex to model based on physical understanding of printing process
- Use direct measurement of absorptance of printed test patterns
  - Macroscopic measurement of average absorptance of periodic test patterns (Pappas, Dong, Neuhoff'93)
    - Set of linear equations; constrained optimization
  - Microscopic measurement of absorptance of individual pixels (Baqai & Allebach'03)
    - Used 4000 dpi drum scanner
    - Alignment using reference marks
    - At 600 dpi, patterns are not stable; need stochastic printer model (mean and variance of dot distribution)

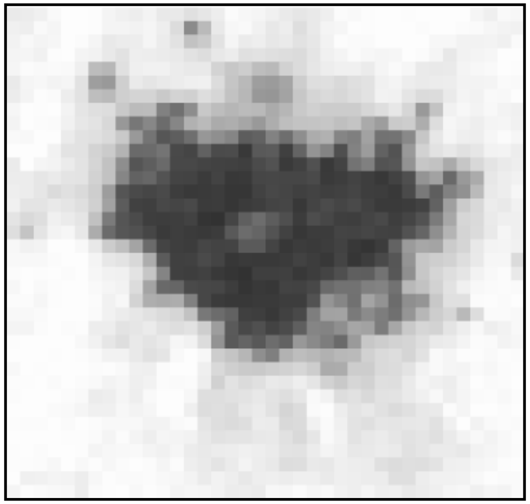
Printer Models



300 dpi

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

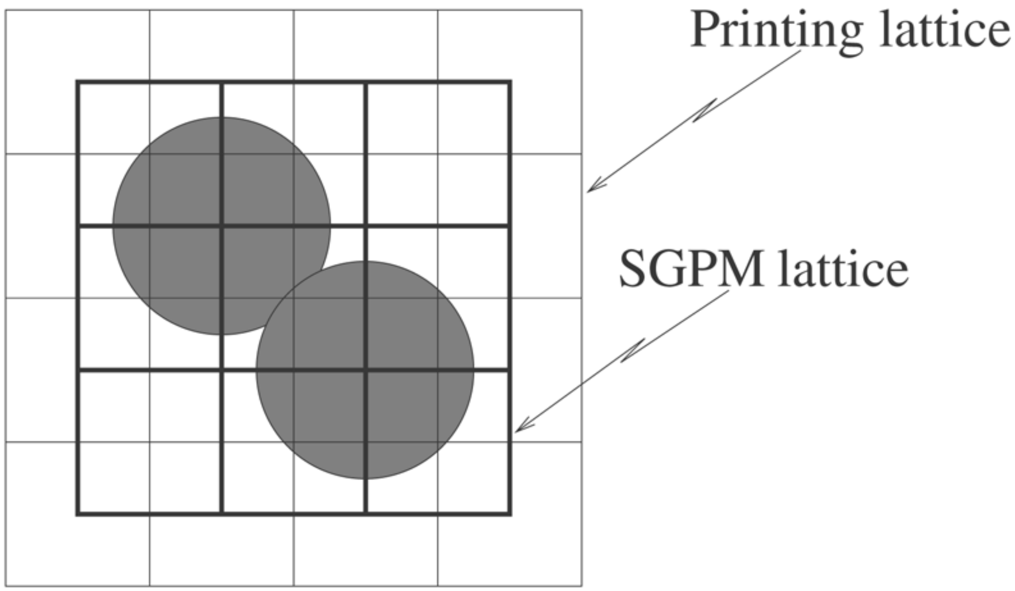
Halftone pattern



600 dpi

Offset-Centered Printer Model

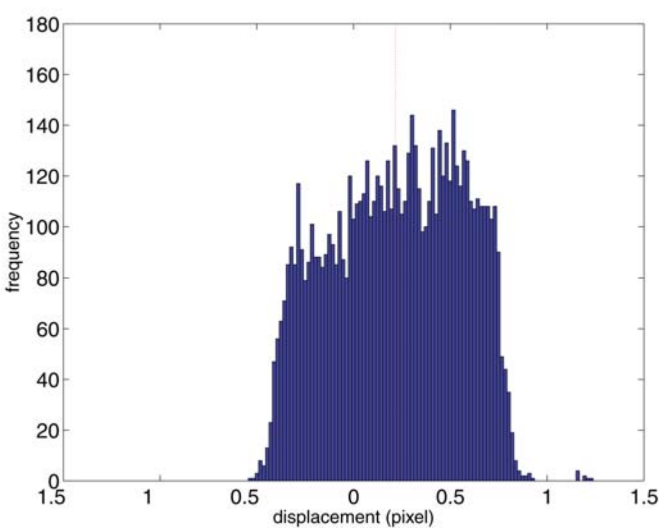
(Wang, Knox, George '94)

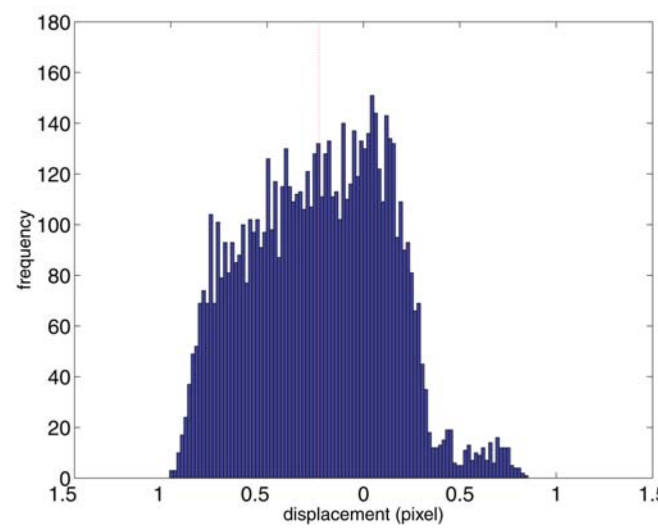


Tabular model has 2^4 entries instead of 2^9

Other Printer Models

- Physics-based electrophotographic printer model (Kacker, Camis, Allebach'02)
- Stochastic dot model (Lin & Wiseman'93) (Lau'99)
- Optical dot gain model (Kruse & Gustavson'96)
- Ink-jet printer model (Lee & Allebach'02)
  - Random dot displacement errors

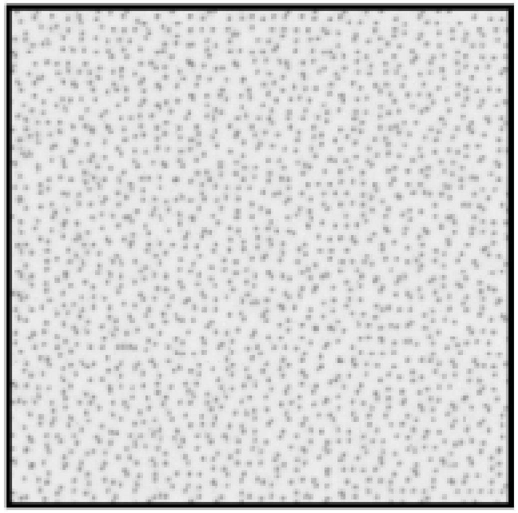




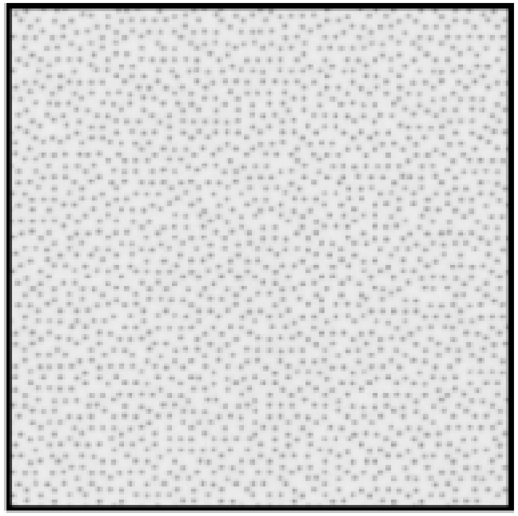
Horizontal displacement for even and odd rows of ink-jet printer

Ink-Jet Printer Model

- Incorporate stochastic nature of model to error metric used by the halftoning technique

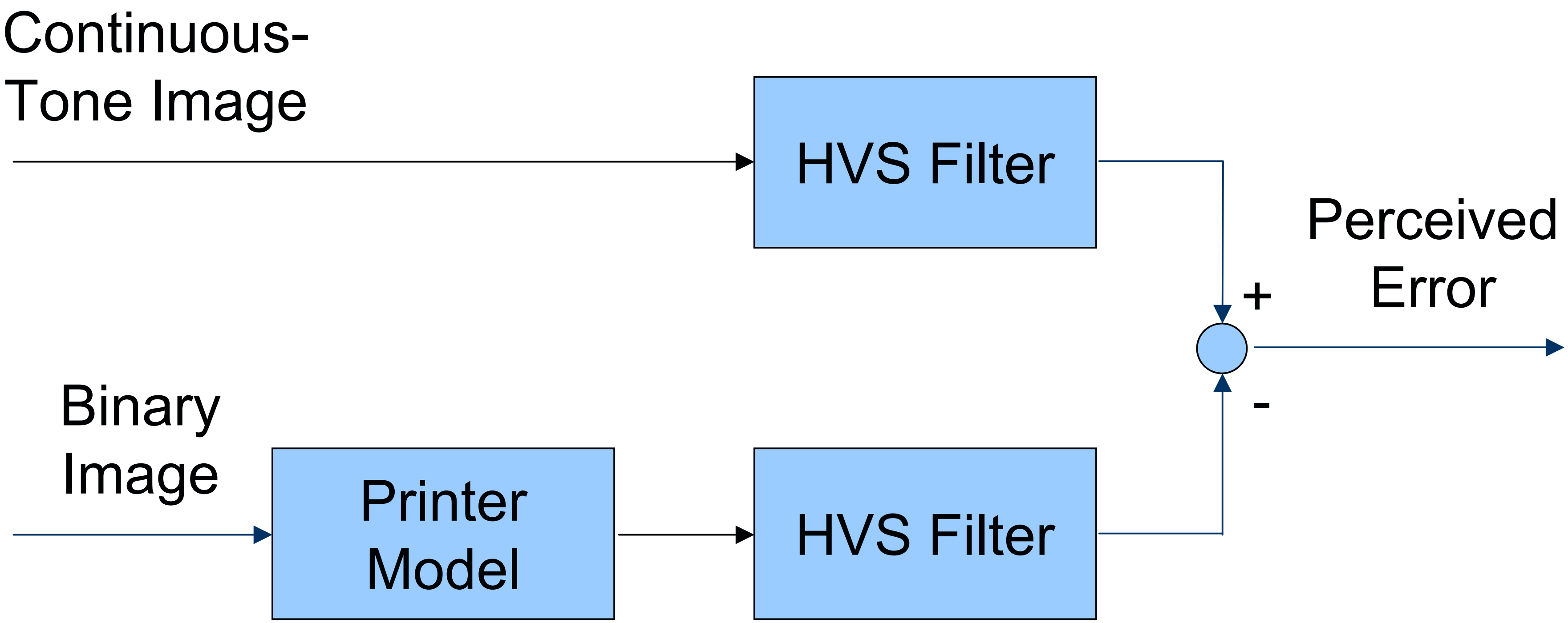


TDED without printer model



TDED with 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

HVS Models

- Scale factor s
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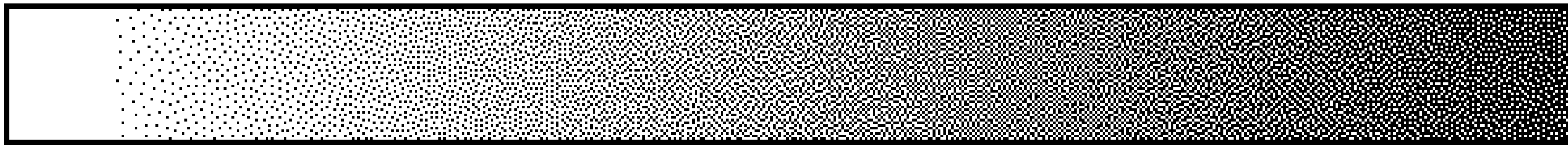
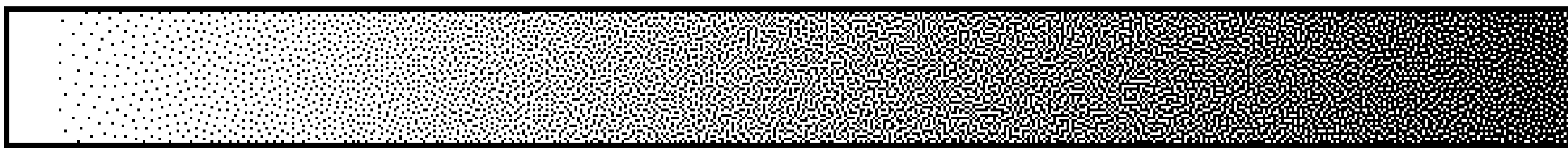
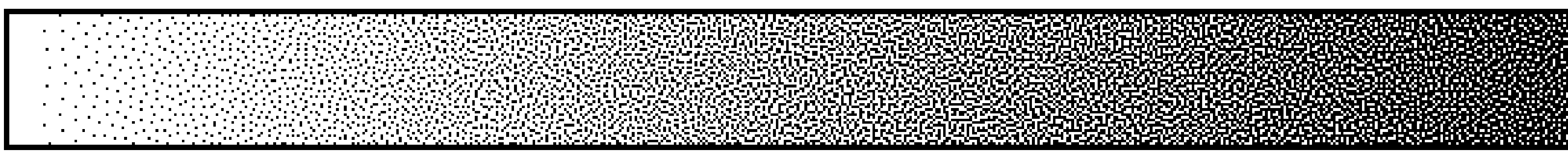
Least-Squares Model-Based Halftoning



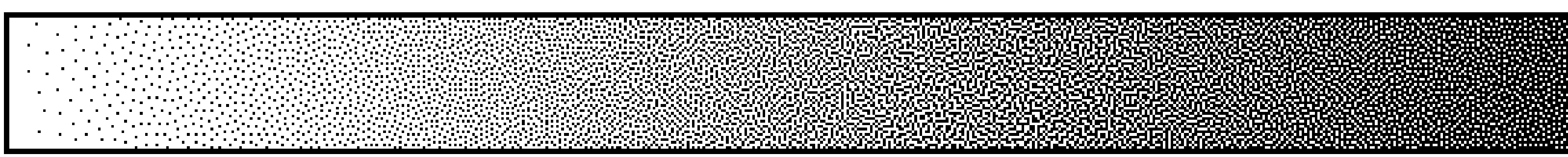
LSMB/DBS, 300 dpi, 0.5 ft



LSMB/DBS, 300 dpi, 1 ft



LSMB/DBS, 300 dpi, 2 ft



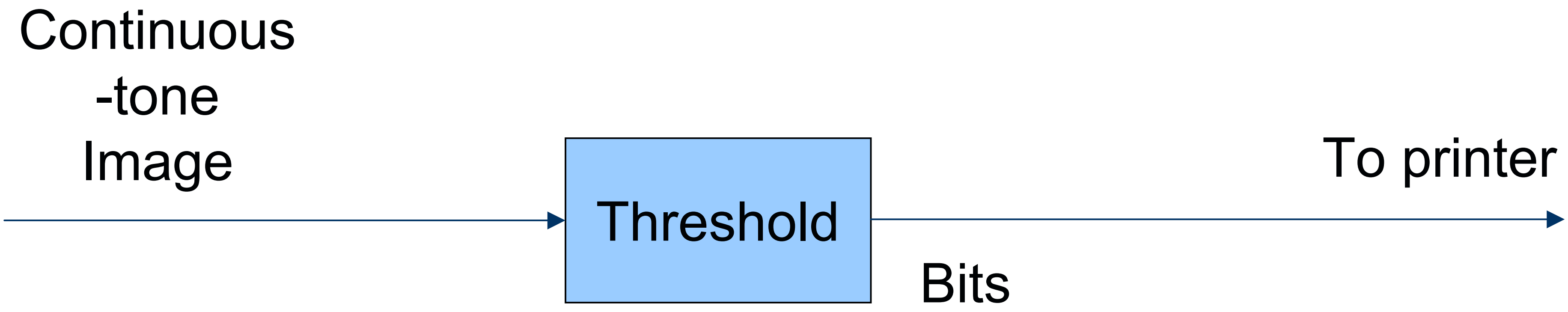
Dual-metric DBS (Kim, Allebach'02)

More Examples (VGs)

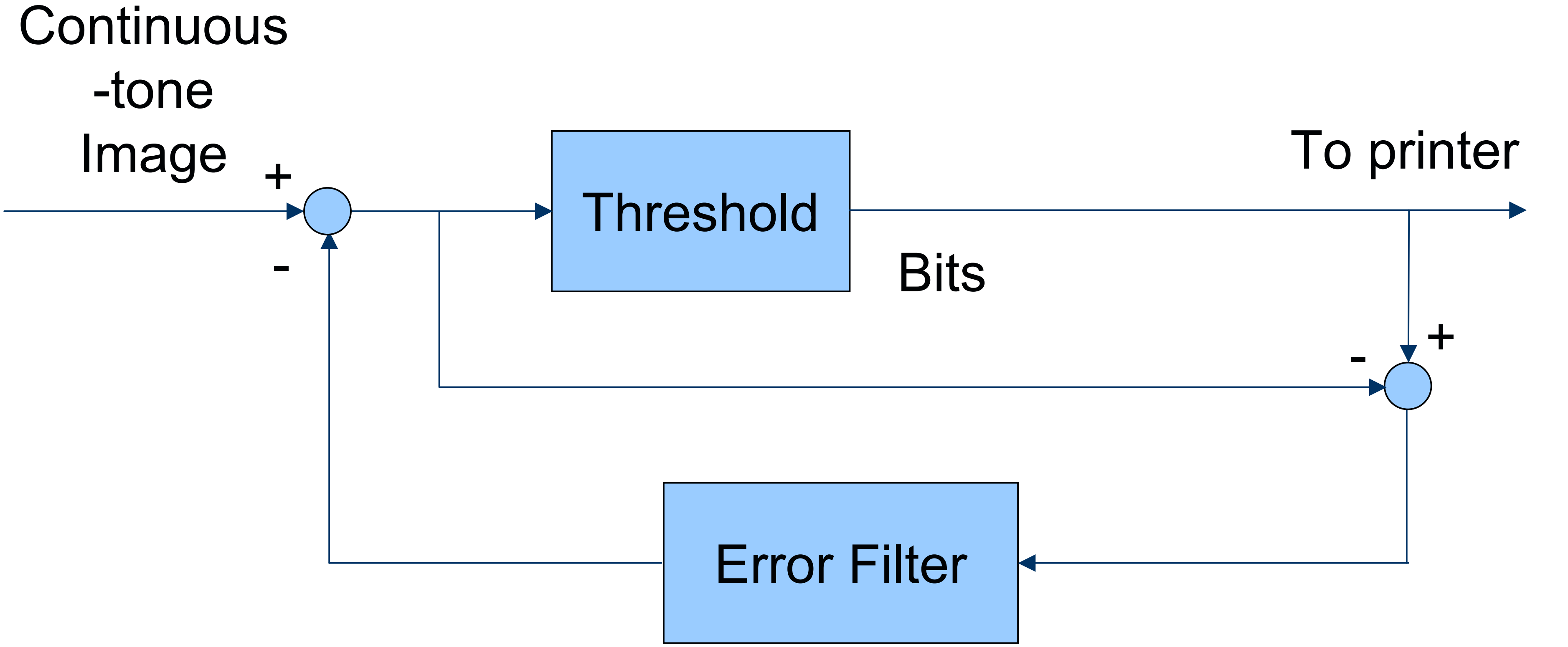
HVS Models

- 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



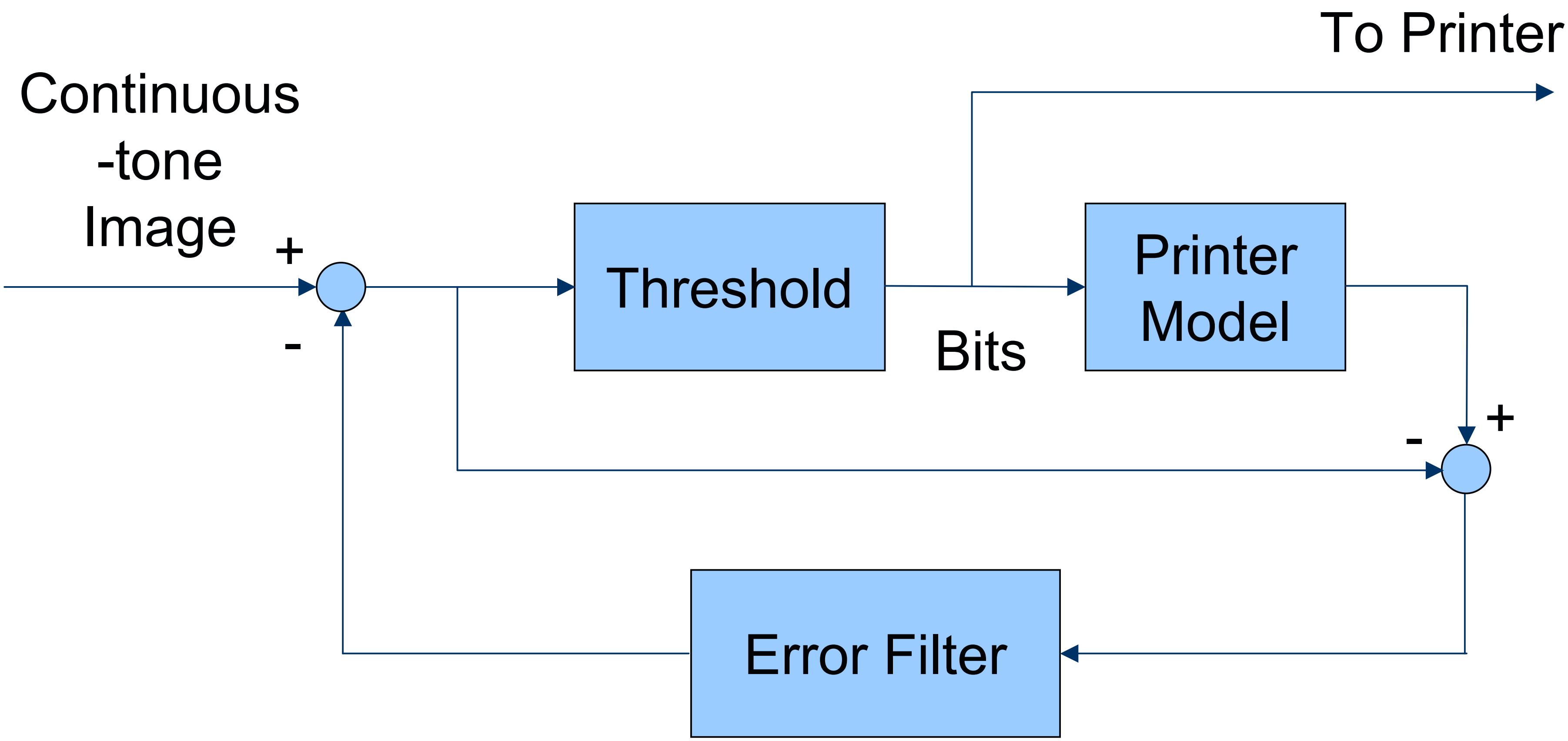
Error Diffusion



Error Diffusion Filter

e	e	e	e	e	e	e	e	e	e	e
e	e	e	e	e	e	e	e	e	e	e
e	e	e	1	3	5	3	1	e	e	e
e	e	e	3	5	7	5	3	e	e	e
e	e	e	5	7	●	?	?	?	?	?
?	?	?	?	?	?	?	?	?	?	?
?	?	?	?	?	?	?	?	?	?	?

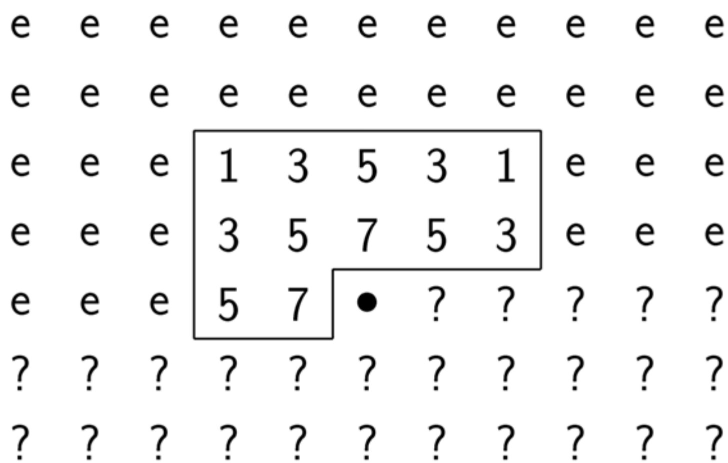
Model-Based Error Diffusion



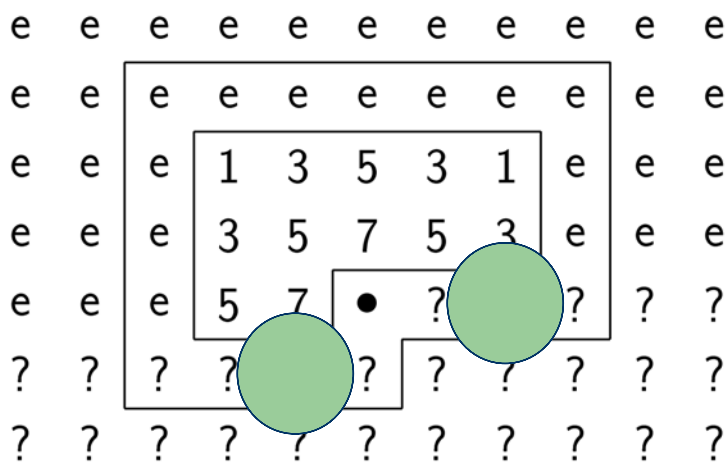
Examples (VGs)

Multi-pass Model-Based Error Diffusion

Standard ED



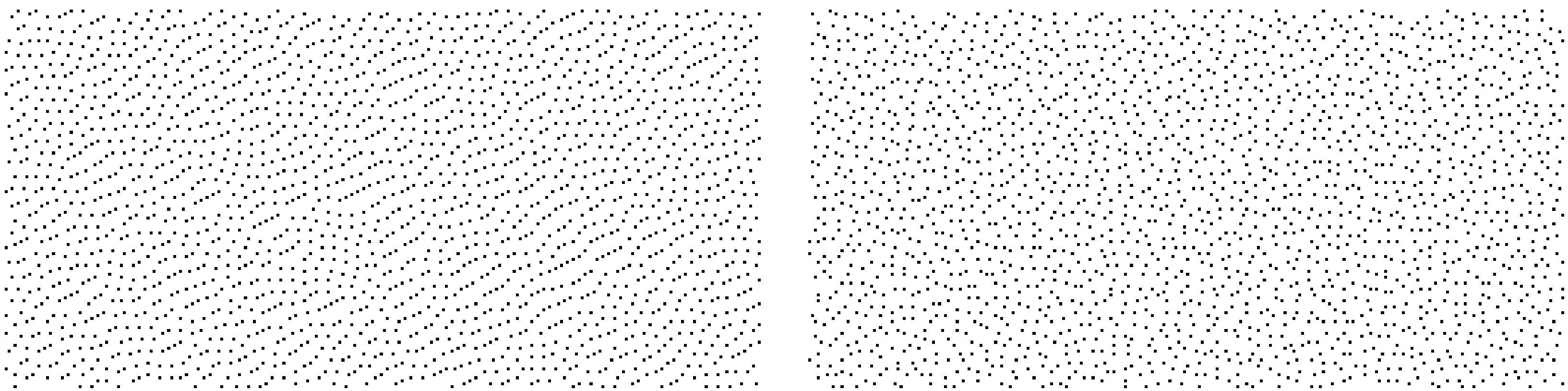
Model-based ED

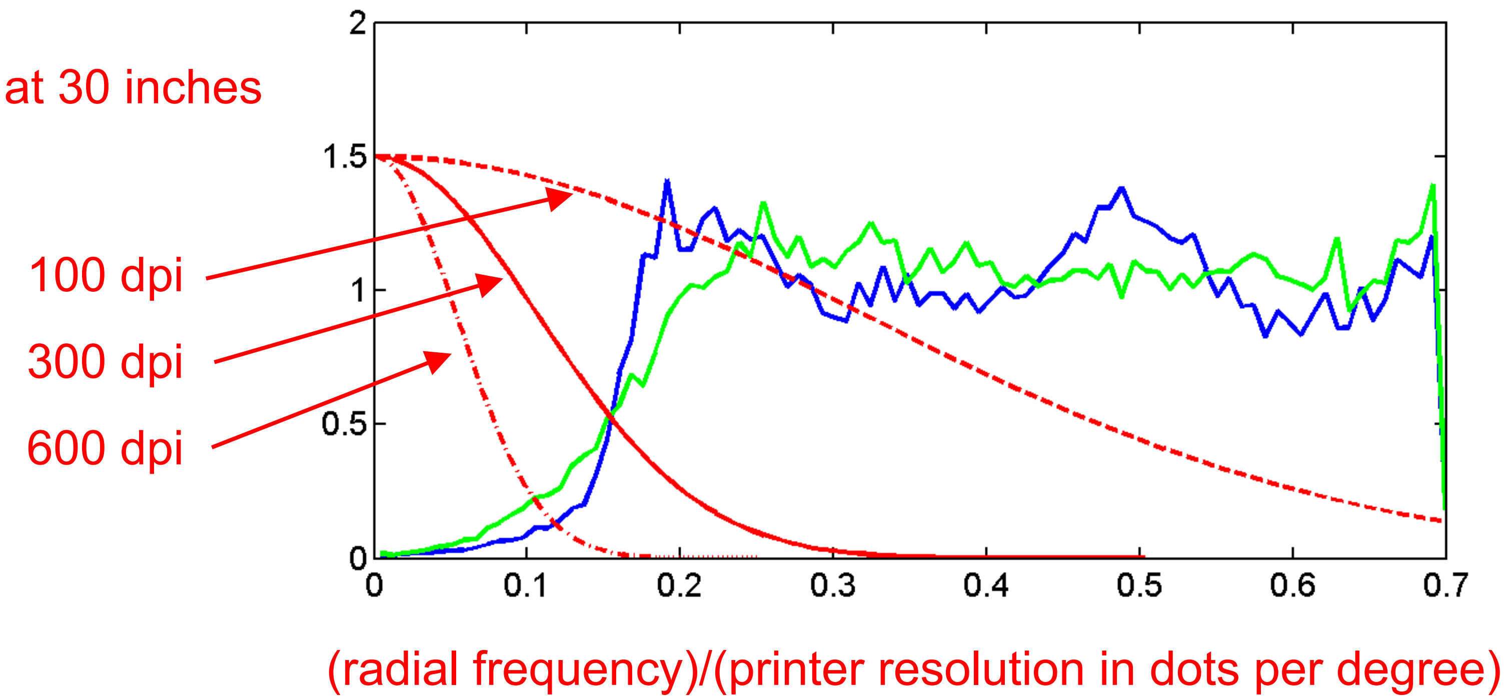


Error Diffusion Modifications

- 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)

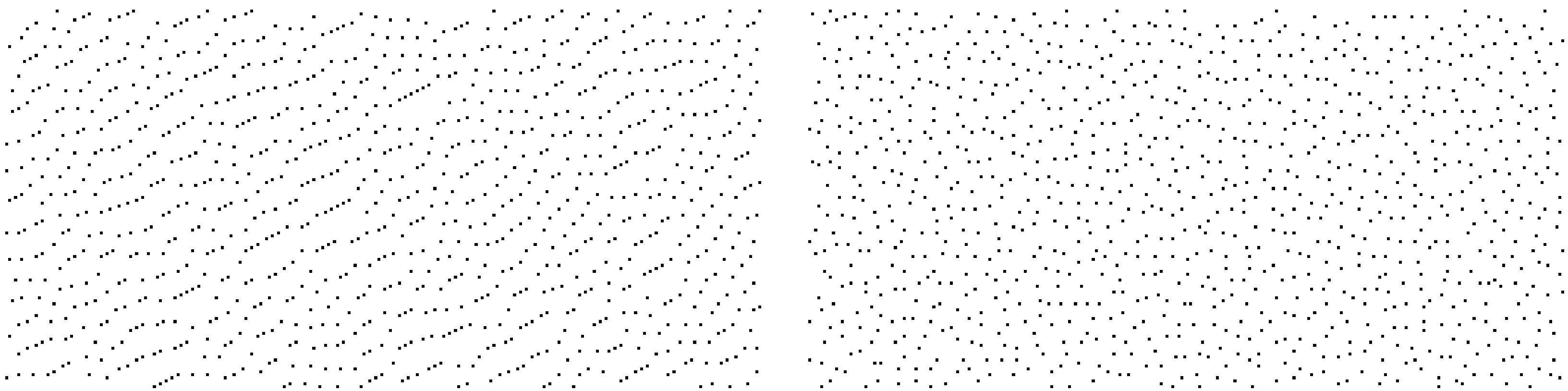
Halftone Quality/Visibility & Radial Spectra

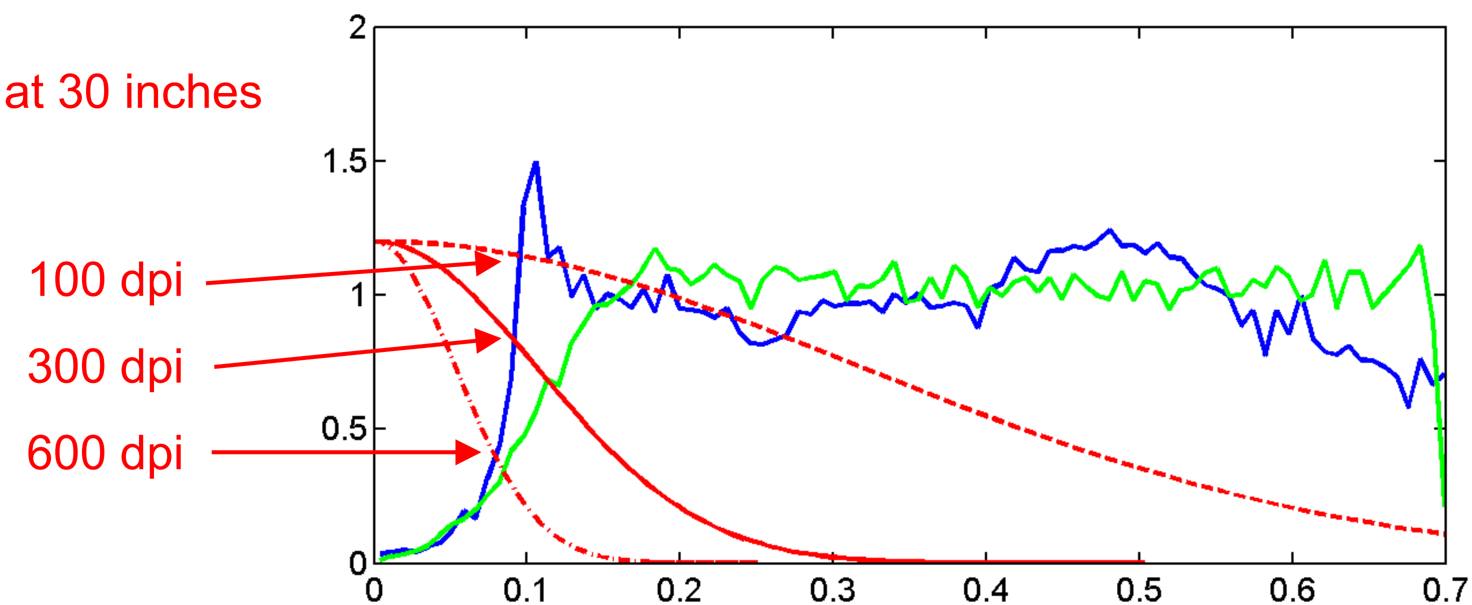




More accurate rendition of halftone patterns (VG)

Halftone Quality/Visibility & Radial Spectra

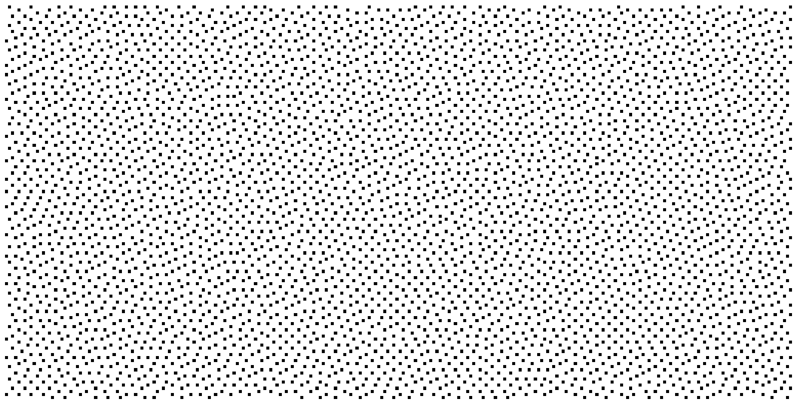


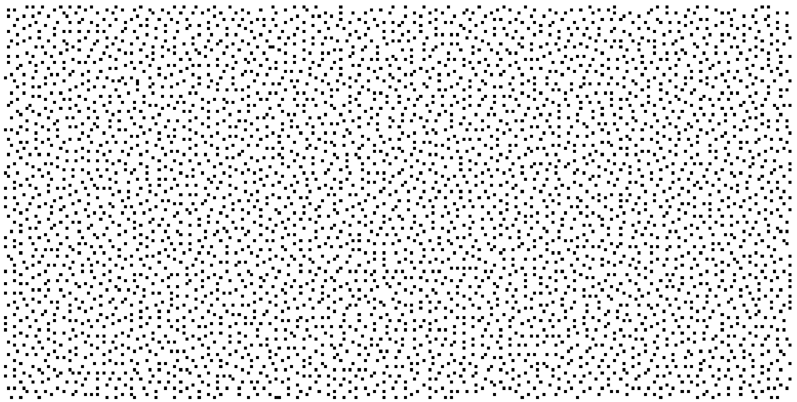


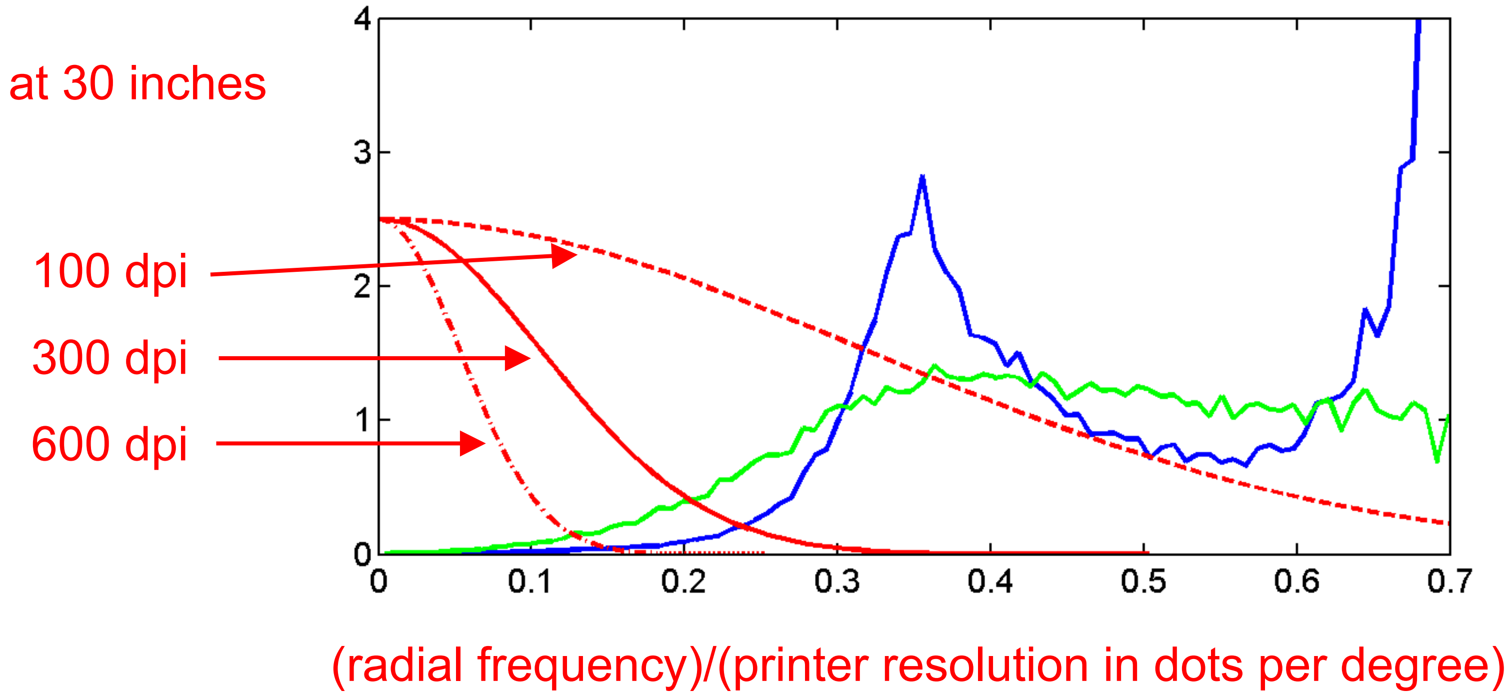
(radial frequency)/(printer resolution in dots per degree)

More accurate rendition of halftone patterns (VG)

Halftone Quality/Visibility & Radial Spectra

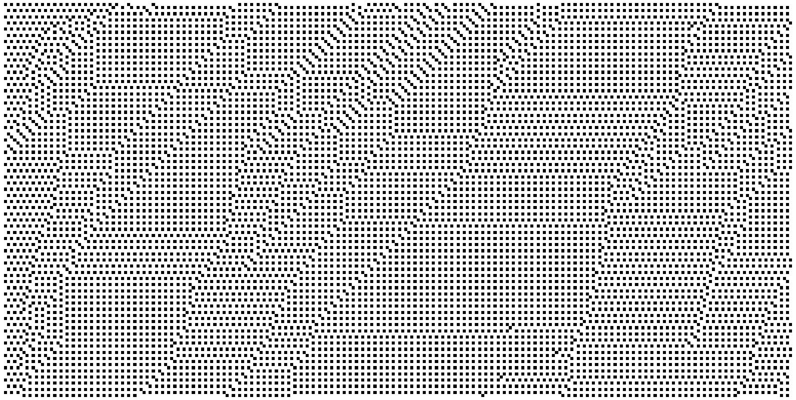


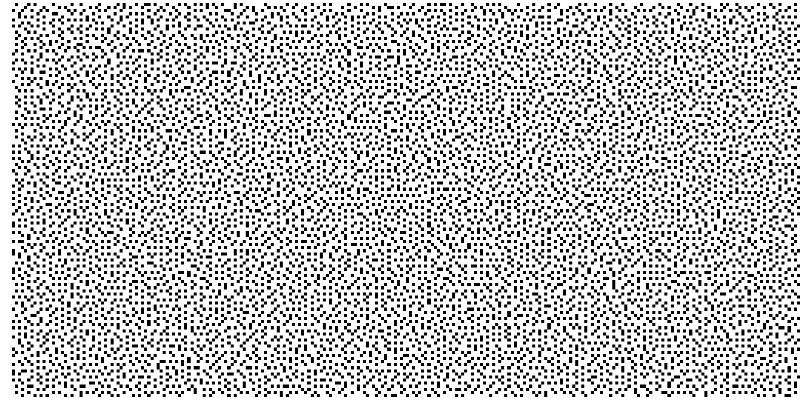


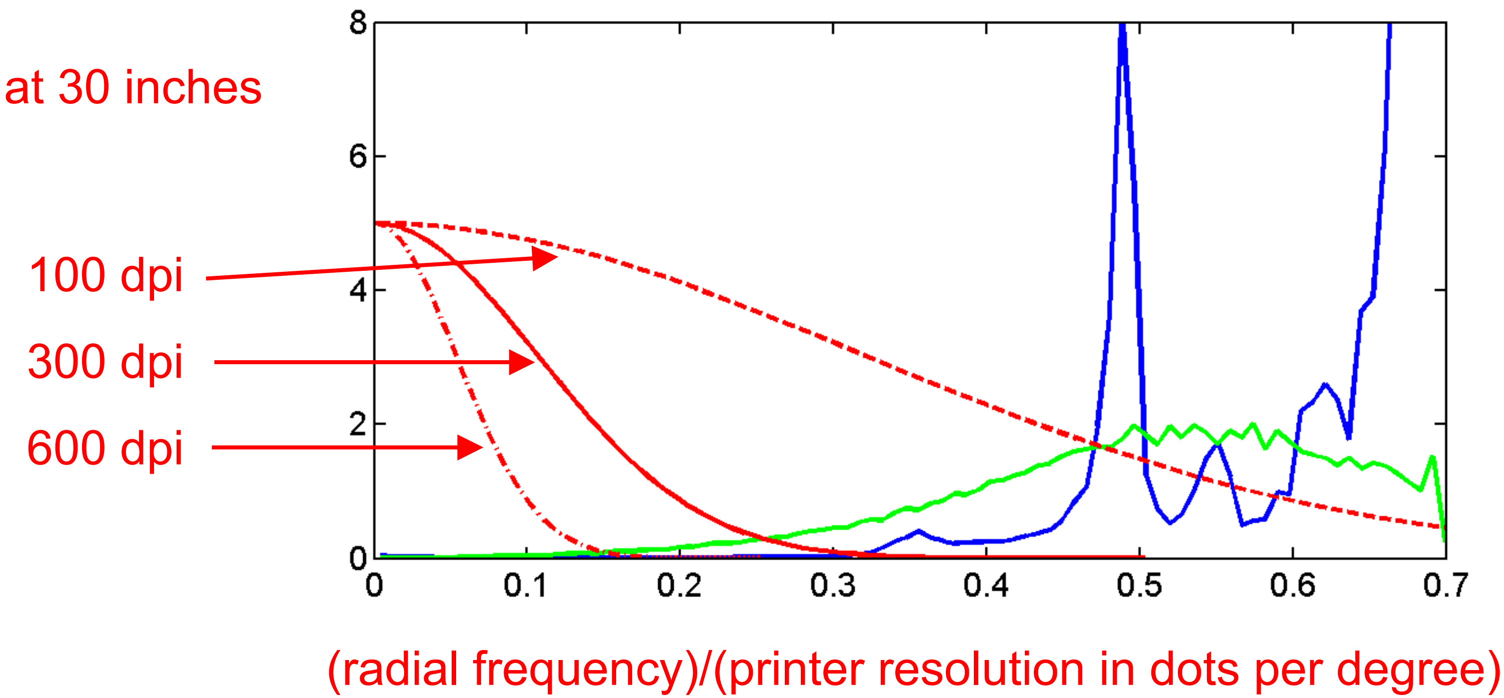


More accurate rendition of halftone patterns (VG)

Halftone Quality/Visibility & Radial Spectra

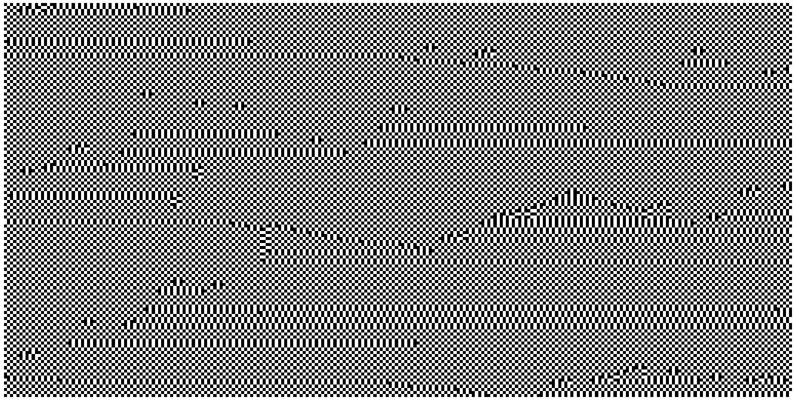


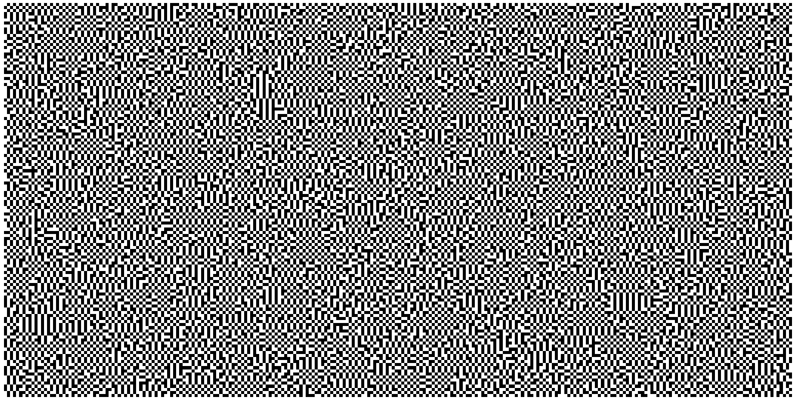


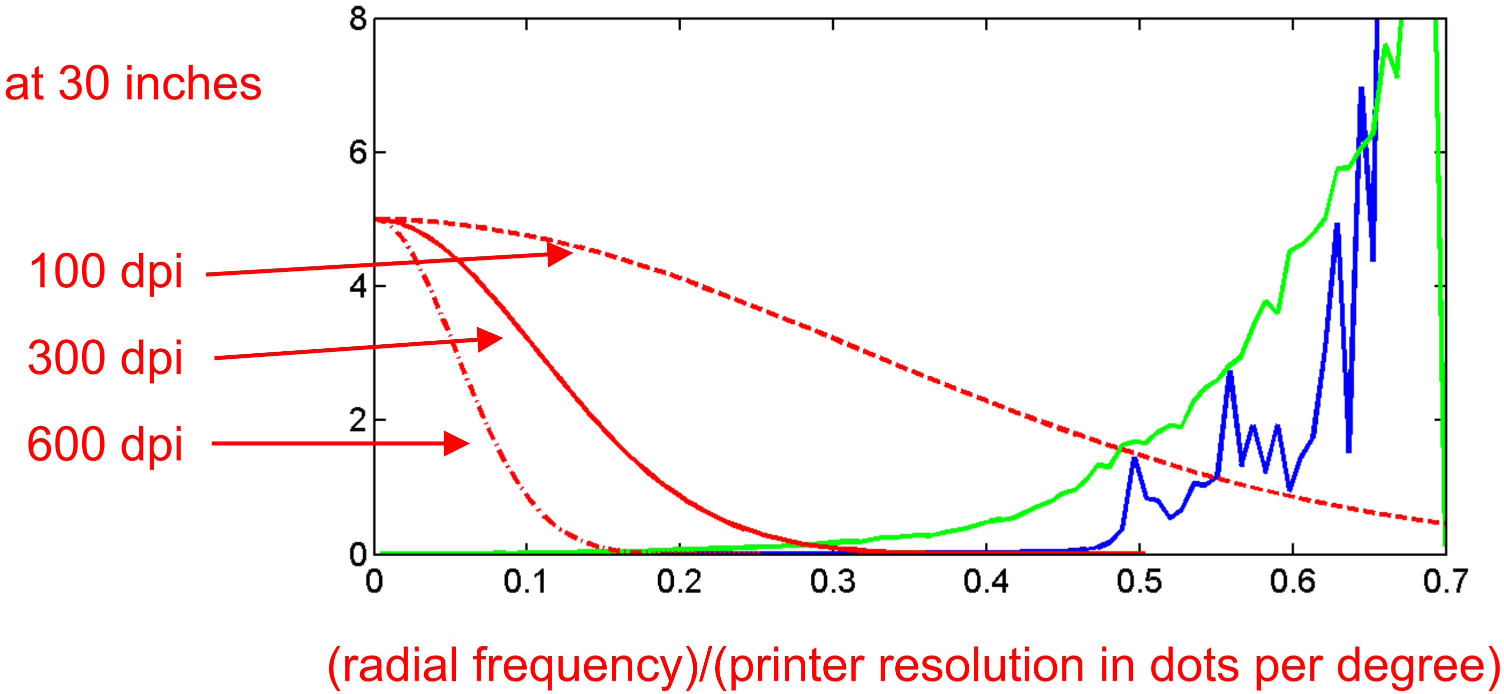


More accurate rendition of halftone patterns (VG)

Halftone Quality/Visibility & Radial Spectra







More accurate rendition of halftone patterns (VG)

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

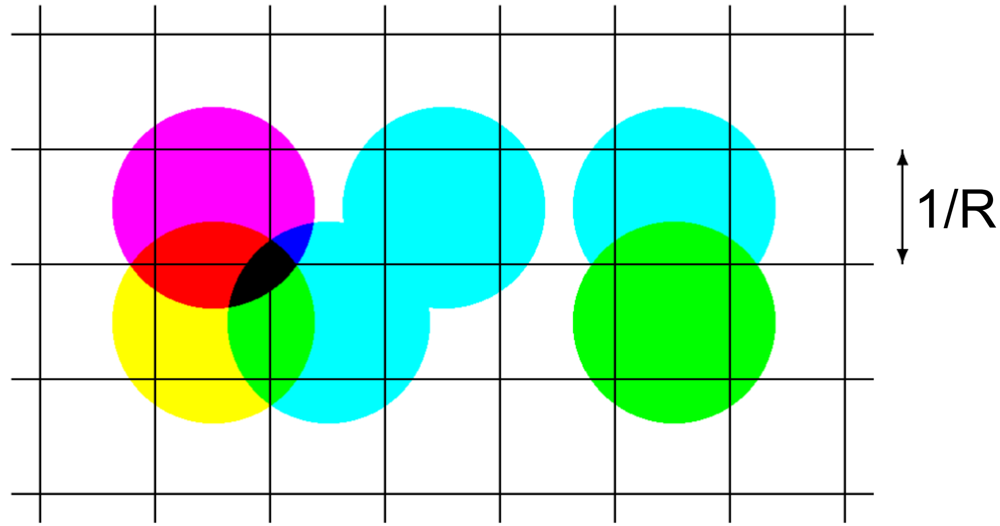
Examples (VGs)

Blue-Noise Screening

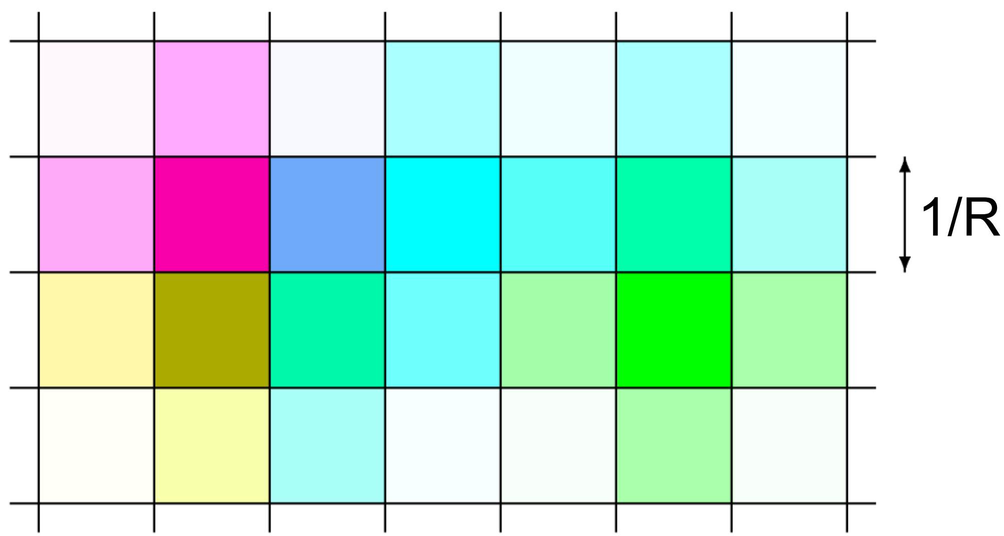
- Attempts to simulate error diffusion
  - Power-spectrum matching (Mitsa & Parker'91)
  - "Void-and-cluster" (Ulichney'93)
  - Gaussian filter used to find largest void and tightest cluster can be interpreted as HVS point spread function
- Can account for printer distortions
- Green-noise screening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

Examples (VGs)

Color Printer Models



Sampled tonescale printer model



Color Halftoning

- Color plane registration
- Imperfect inks
- Tabular printer model impractical
  - Table of 3 X 3 patterns has 8^9 entries (CMYK 16^9 entries)
- Error diffusion instabilities

Examples (VGs)

Digital Halftoning

- Multidisciplinary area of research
  - Signal processing
  - Mechanical engineering
  - Psychophysics
- Modeling (exploiting!)
  - Signal characteristics
  - Limitations of rendering device
  - Limitations of human visual system

Digital Halftoning

- Open areas
  - Eye models
  - Printer models
  - Display models
  - Compression
  - Watermarking