Signal and Image Processing Seminar

DESIGN AND QUALITY ASSESSMENT OF FORWARD AND INVERSE ERROR DIFFUSION HALFTONING ALGORITHMS

Ph.D. Defense

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31 July 1998

OUTLINE

- Introduction to halftoning
- Visual quality metrics for forward and inverse halftoning
  - Human visual system
  - Weighted noise metric (WSNR)
  - Modeling other distortions
- Halftoning by error diffusion
  - Linear gain model
  - Modified error diffusion
  - Noise metric
  - Tonality metric
- Inverse halftoning
  - Algorithm design and results
  - Modeling inverse halftoning
  - Quality metrics
- Rehalftoning and interpolation
- Contributions

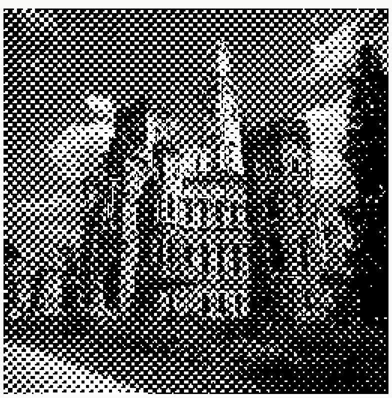
INTRODUCTION: HALFTONING

- Was analog, now digital image processing
- Wordlength reduction for images
  - 8-bit to 1-bit for grayscale
  - 24-bit RGB to 8-bit for color displays
  - 24-bit RGB to CMY for color printers
- Applications
  - Printers
  - Digital copiers
  - Liquid crystal displays
  - Video cards
- Halftoning methods
  - Screening
  - Error diffusion
  - Direct binary search
  - Hybrids

EXAMPLE HALFTONES

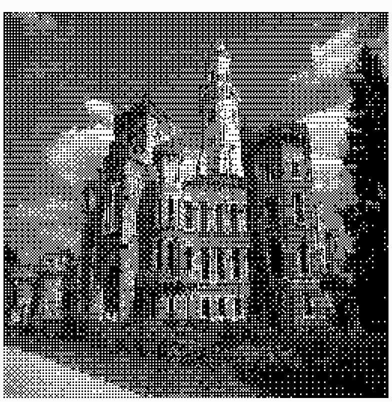
Original image

Direct binary search



Clustered dot screen

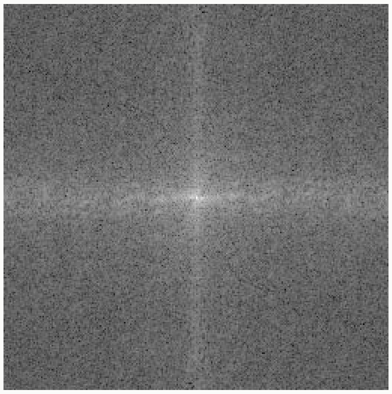
Error diffusion I



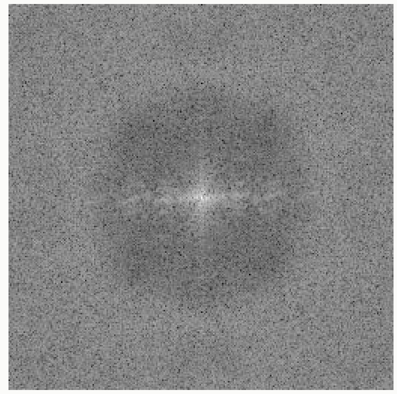
Dispersed dot screen

Error diffusion II

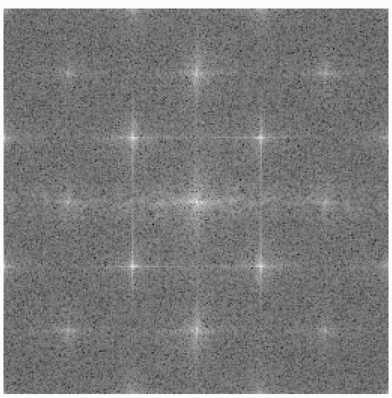
FOURIER TRANSFORMS



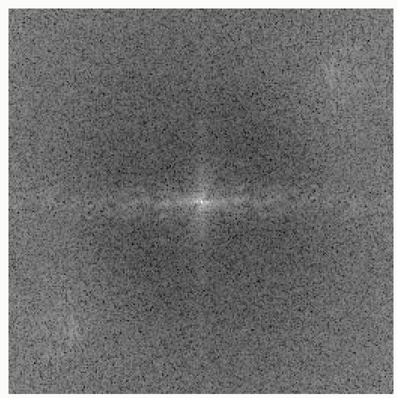
Original image



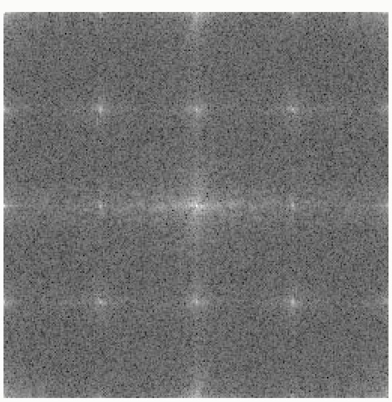
Direct binary search



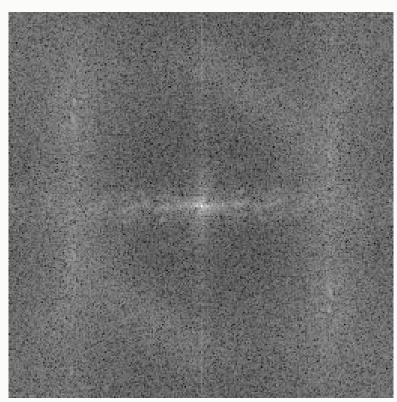
Clustered dot screen



Error diffusion I



Dispersed dot screen



Error diffusion II

PROBLEMS TO BE SOLVED

- Visual quality metrics for forward and inverse halftones
  - Quantify frequency distortion
  - Quantify artifacts
  - Quantify quantization noise
- Modeling error diffusion
  - Develop tractable model
  - Demonstrate accuracy of model
  - Use model to design applications
- Inverse halftoning
  - Develop efficient algorithm
  - Develop model for inverse halftoning

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HUMAN VISUAL SYSTEM (HVS)

- Non-linear, spatially varying
- Assuming linearity, spatial invariance explains [Cornsweet 1970]
  - Mach band effect
  - Apparent brightness *vs.* intensity

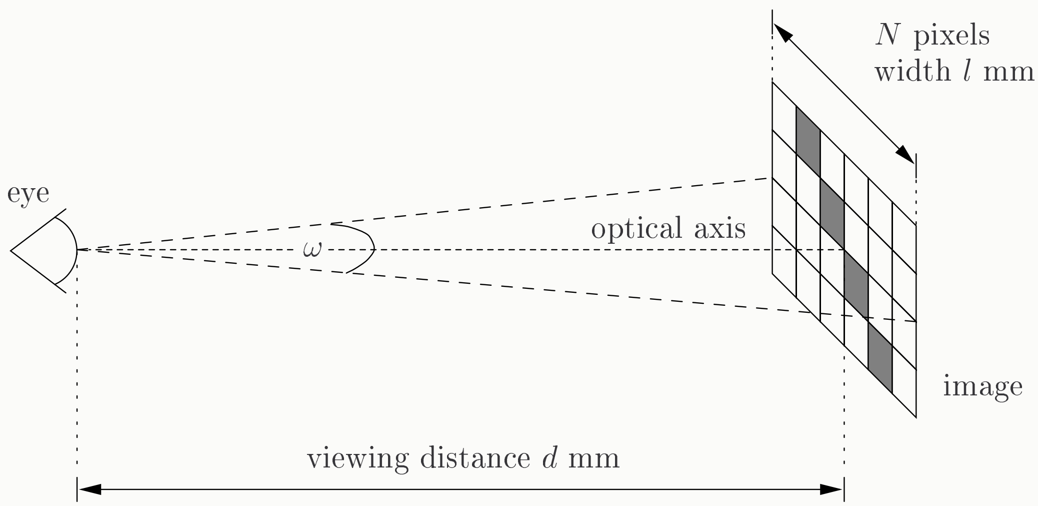
White noise
SNR = 10 dB

Blue (highpass) noise
SNR = 10 dB

- Weight by spatial frequency to quantify visual impact of noise

ANGULAR FREQUENCY

- Sensitivity depends on angular frequency subtended at eye
- Compute angular frequency from image size (pixels), printed image size (mm), viewing distance (mm)



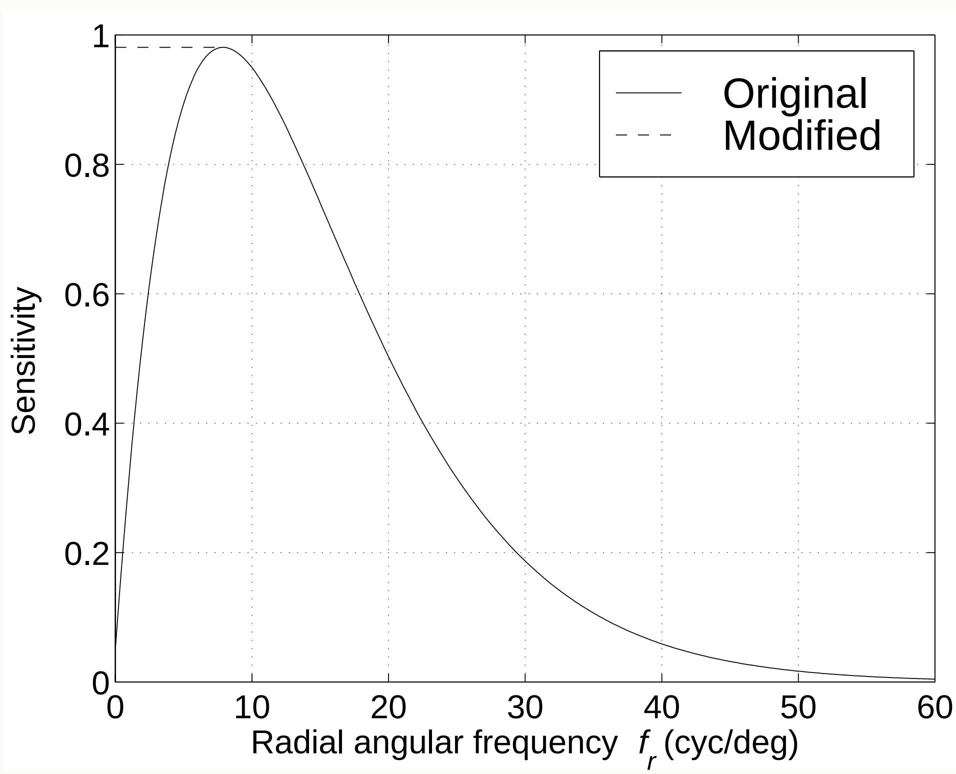
- At Nyquist frequency

$$f_a = \frac{N\pi d}{360 l} \quad \text{cycles/degree}$$

CONTRAST SENSITIVITY (CSF)

- Minimum contrast to distinguish sine grating from uniform field
- Model [Mannos & Sakrison 1974]
- Modification [Mitsa & Varkur 1993]

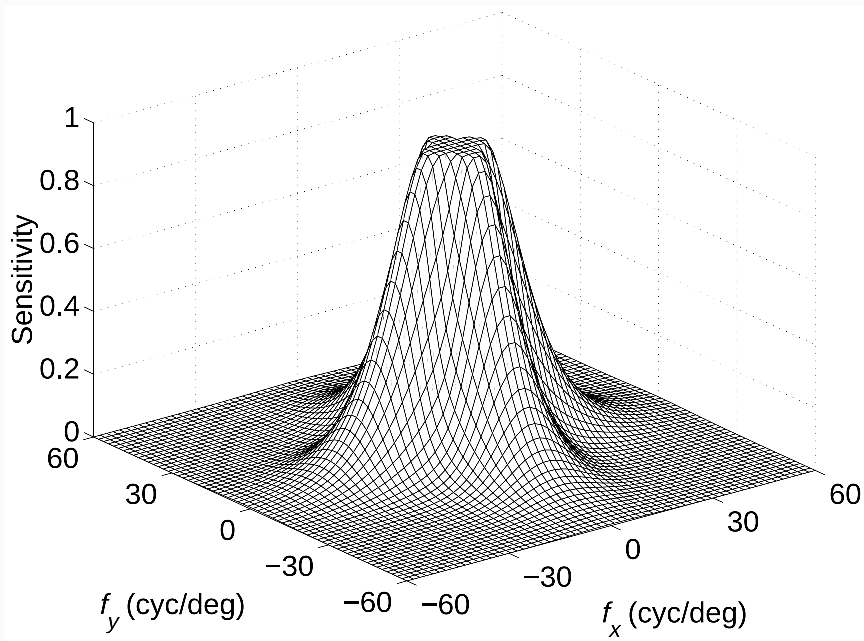
$$\mathrm{CSF} = 2.6\,(0.02 + 0.1 f_a)\, e^{-(0.1 f_a)^{1.1}}$$



- Orientation-independent

WEIGHTED SNR METRIC

- Include orientation (angular dependence) in CSF [Sullivan, Miller & Pios 1993]

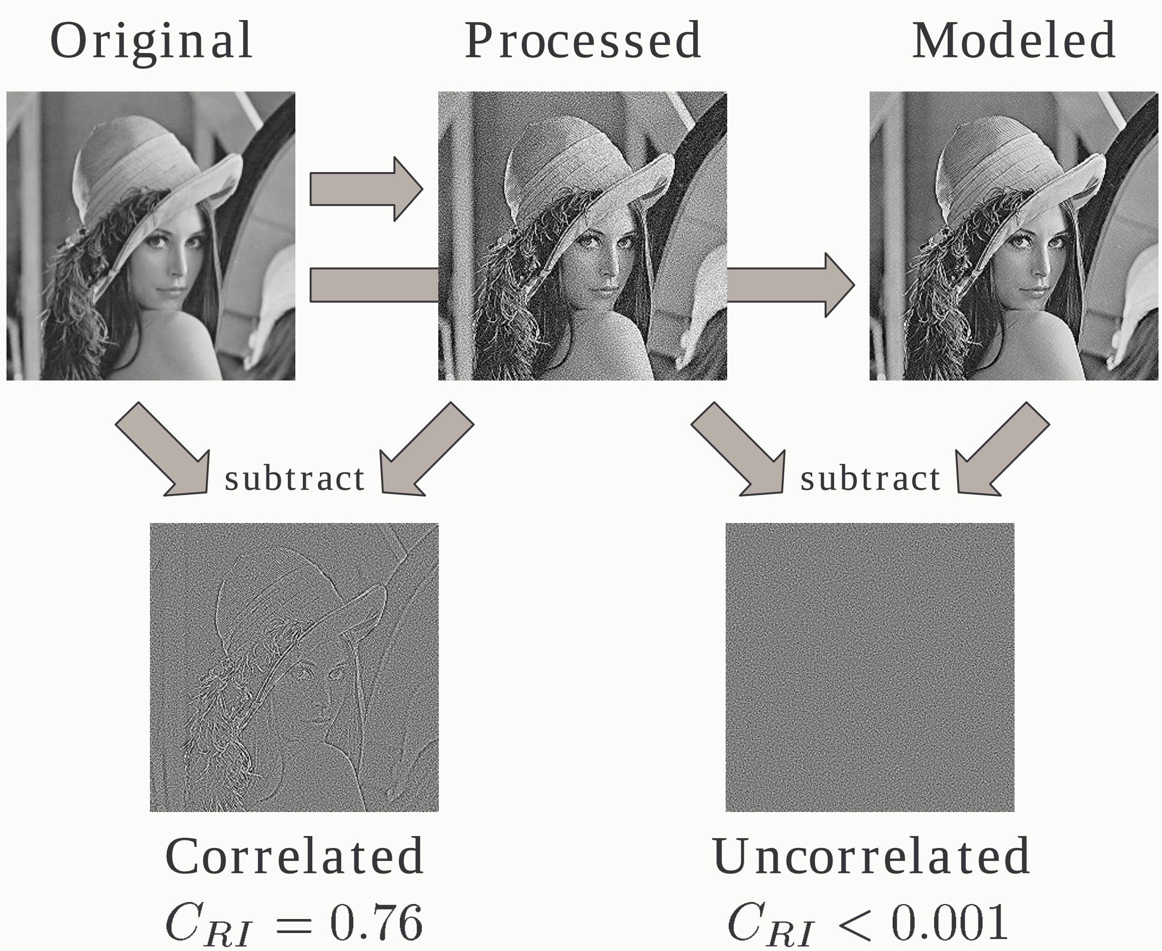


- Compute weighted signal-to-noise ratio between original image *x* and processed image *y*

$$\mathrm{WSNR} = 10\log_{10}\left(\frac{\sum|\mathrm{CSF}\times X(u,v)|^2}{\sum|\mathrm{CSF}\times(X(u,v)-Y(u,v))|^2}\right)$$

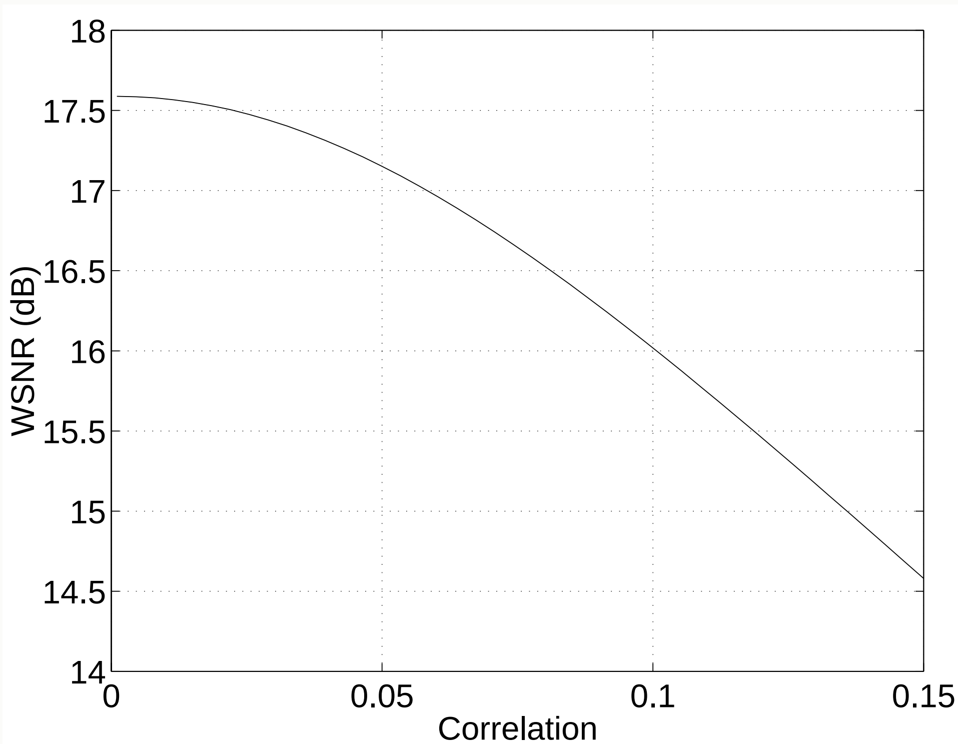
MODELING DISTORTION

- WSNR is a *noise* metric
  - Difference (residual) between original and processed images must be noise
  - Model, compensate for other distortions
  - Measure correlation of residual and original; for accuracy, $C_{RI} < 0.020$



WSNR vs. CORRELATION

- WSNR increasingly inaccurate as correlation increases



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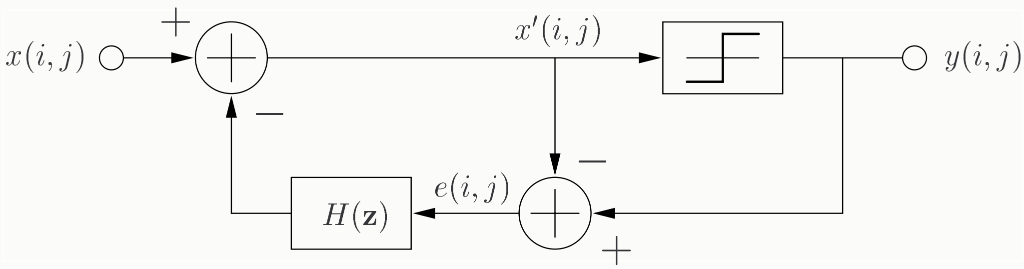
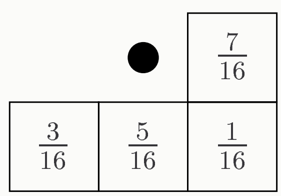
ERROR DIFFUSION

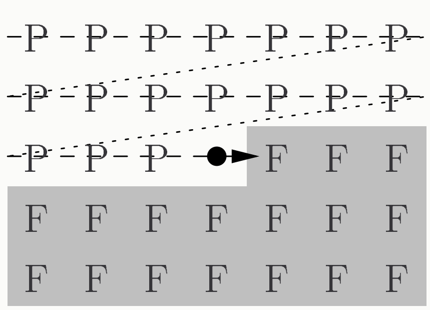
- 2-D delta-sigma modulator
- Noise shaping feedback coder



- Error filter



- Raster scan order



P = Past
F = Future

- Serpentine scan also used

ERROR DIFFUSION (contd.)

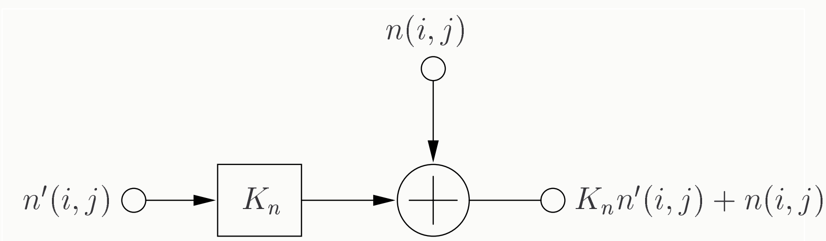
- Quantizer

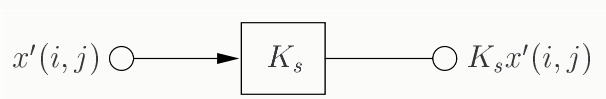
$$y(i,j) = \begin{cases} 0, & x'(i,j) < 0.5 \\ 1, & x'(i,j) \geq 0.5 \end{cases}$$

- Governing equations

$$\begin{aligned} e(i,j) &= y(i,j) - x'(i,j) \\ x'(i,j) &= x(i,j) - h(i,j) * e(i,j) \end{aligned}$$

- Non-linearity difficult to analyze
- Linearize quantizer
  [Kite, Evans, Bovik & Sculley 1997]

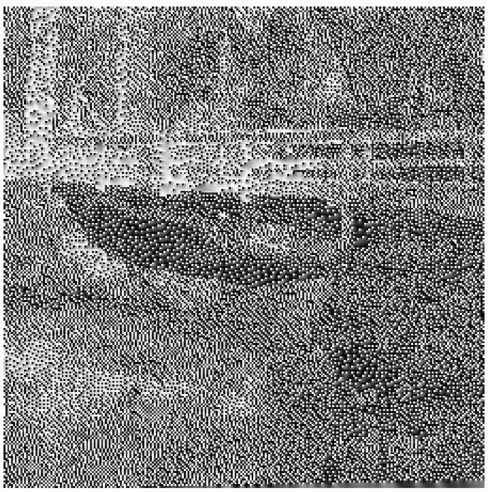




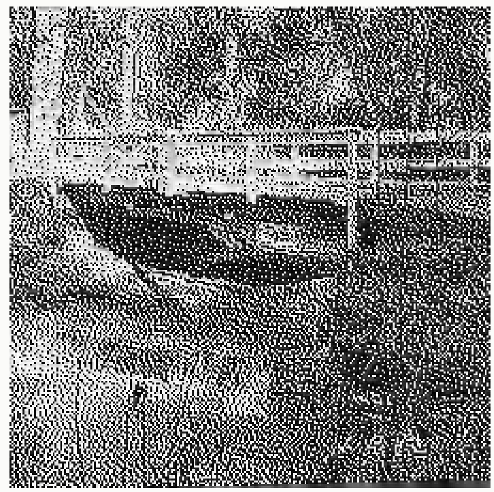
- Separate signal and noise paths
  [Ardalan & Paulos 1987]

LINEAR GAIN MODEL

- Quantization error correlated with input [Knox 1992]



Floyd-Steinberg



Jarvis, Judice & Ninke

- Least squares fit of quantizer input to output defines signal gain

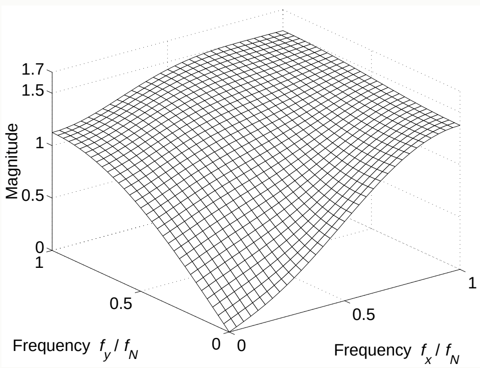
$$K_s = \frac{E[|x'(i,j)|]}{2E[x'(i,j)^2]}$$

- Signal gain: $K_s \approx \text{constant}$
- Noise gain: $K_n = 1$

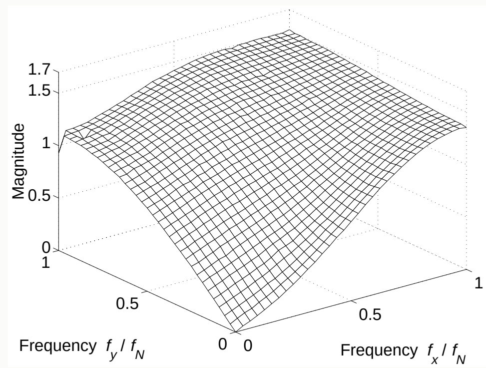
GAIN MODEL PREDICTIONS

- Noise transfer function (NTF)

$$\mathrm{NTF} = 1 - H(\mathbf{z})$$



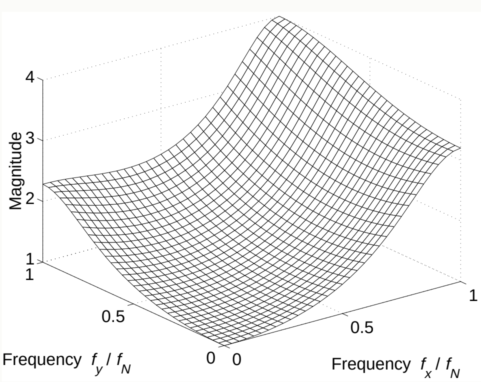
Predicted



Measured

- Signal transfer function (STF)

$$\mathrm{STF} = \frac{K_s}{1 + (K_s - 1)H(\mathbf{z})}$$



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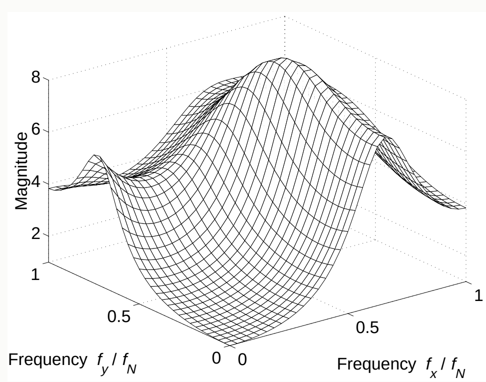
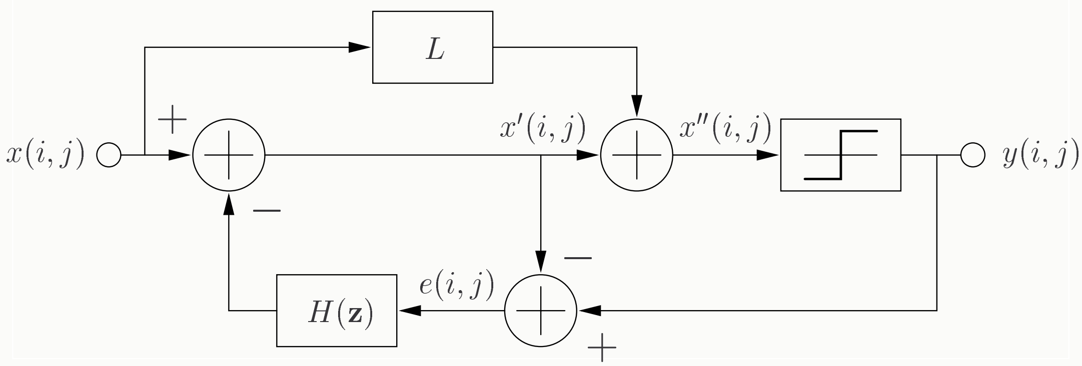


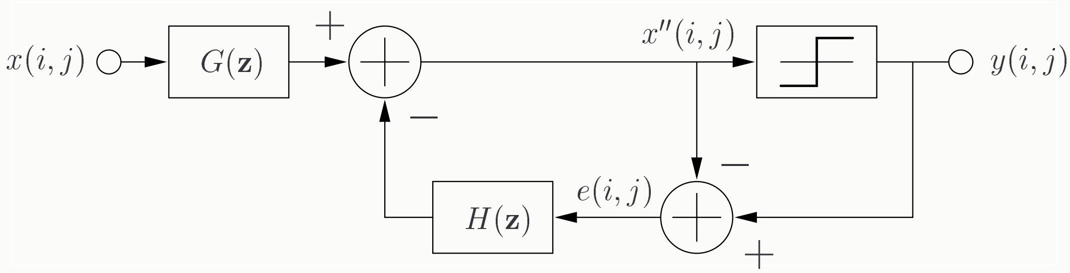
Jarvis *et al.*

MODIFIED ERROR DIFFUSION

- Efficient method of adjusting sharpness [Eschbach & Knox 1991]



- Equivalent circuit: pre-filter

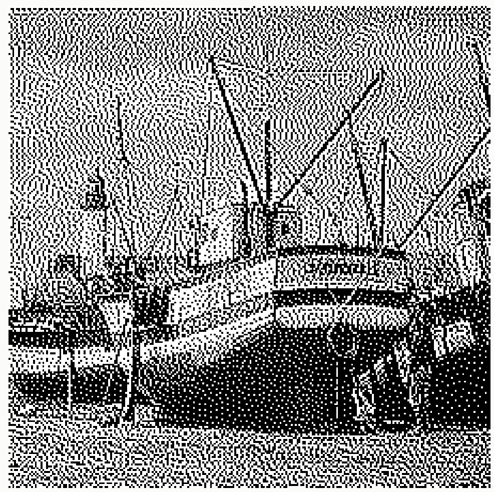


$$G(\mathbf{z}) = 1 + L\,(1 - H(\mathbf{z}))$$

UNSHARPENED HALFTONES

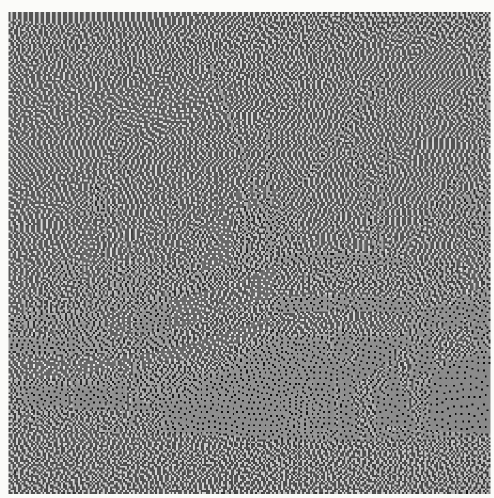
- If $L = \frac{1 - K_s}{K_s}$ then $\text{STF} = 1$ (flat)

Original image



Jarvis halftone

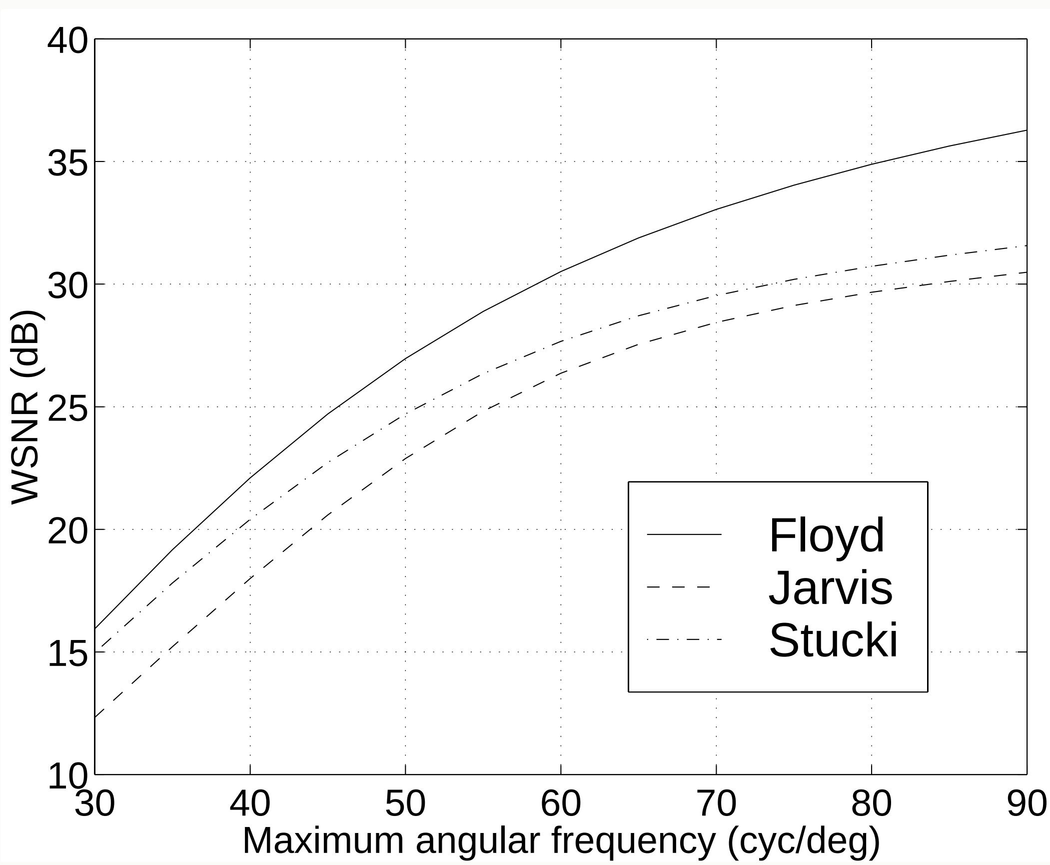
Unsharpened halftone



Residual

OBJECTIVE NOISE METRIC

- To find WSNR
  - Compute signal gain K_s, or use average
  - Generate unsharpened halftone using modified error diffusion
  - Compute WSNR of unsharpened halftone relative to original image



OBJECTIVE TONALITY METRIC

- Limit cycles cause visual ‘worm’ artifacts [Fan & Eschbach 1994]
- Larger filters and serpentine scan result in lower tonality
- Define tonality metric
  - Measure total distortion of sine grating

$$T = \left[\frac{1}{Y(e^{j\omega_f})Y^*(e^{j\omega_f})} \sum_{\omega \in \{\omega_d\}} Y(e^{j\omega})Y^*(e^{j\omega}) \right]^{\frac{1}{2}}$$

  - Average T over grating frequencies
- Agrees with visual results
  - Correct ordering of error filters
  - Serpentine scan less tonal

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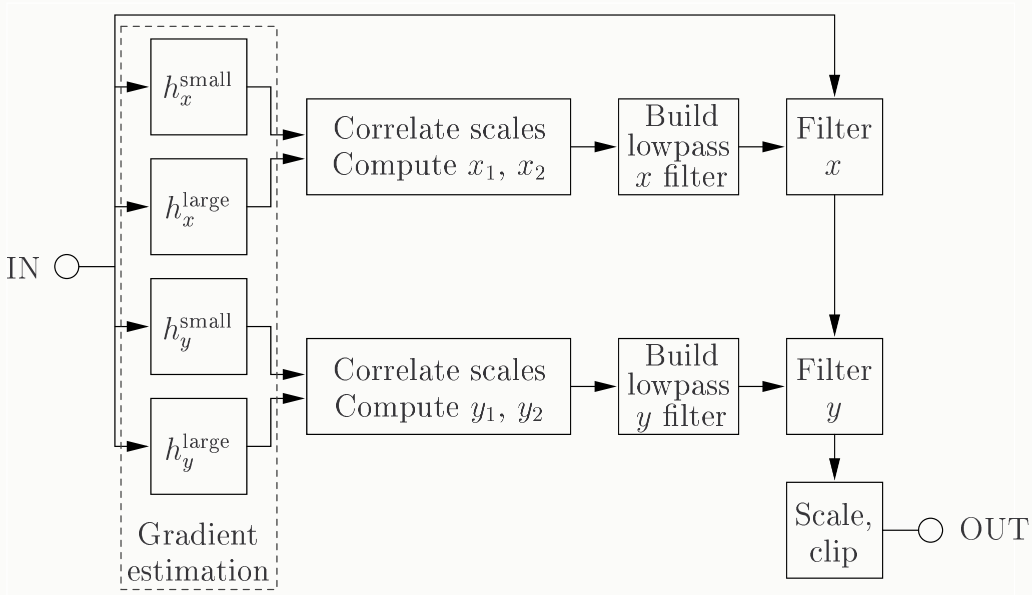
INVERSE HALFTONING

- Attempt to recover grayscale images from halftones
- Applications
  - Digital copiers
  - Scanner software
- Many approaches:
  - Bayesian estimation [Schweizer & Stevenson 1993]
  - Vector quantization [Ting & Riskin 1994]
  - Projection onto convex sets [Hein & Zakhor 1995]
  - Lowpass smoothing and nonlinear filtering [Wong 1995]
  - Wavelet denoising [Xiong, Orchard & Ramchandran 1997]
- Most are iterative and slow
- Best results from wavelet scheme

PROPOSED METHOD

- Apply anisotropic diffusion [Kite, Damera-Venkata, Evans & Bovik 1998]
  - Estimate image gradients
  - Compute diffusion coefficient
  - Smooth within areas, preserve edges
- Unique environment
  - Highpass noise, SNR ≈ 3 dB
  - Tonal
- Solution
  - Specialized gradient estimator
  - Correlate estimate across scales [Mallat & Zhong 1992]
  - Separable—smooth parallel to edges
- Local operations
  - Low memory requirement
  - Low computational cost

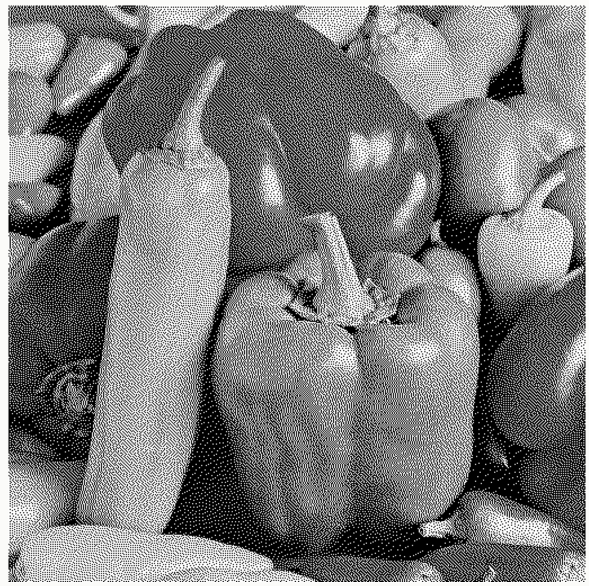
PROPOSED METHOD (contd.)



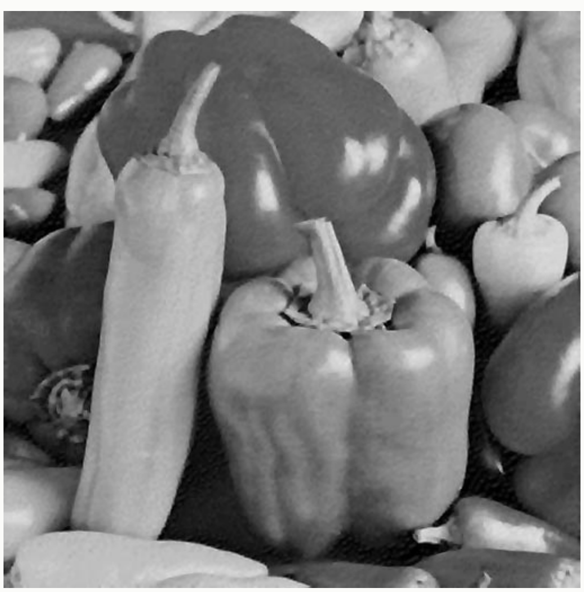
- Estimate gradients at two scales
  - 7×7, 5×5 FIR filters
  - Integer additions only
- Correlate gradients across scales
  - 5 dB improvement in gradient SNR
- Construct parametric smoother
  - 7×7 separable FIR filter
  - Family optimized for halftones
  - Quantized integer coefficients

INVERSE HALFTONE RESULTS

Original image



Halftone

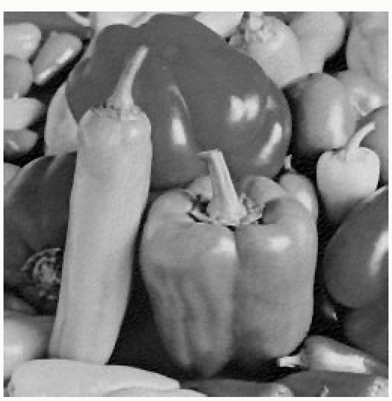


Proposed method

Wavelet method

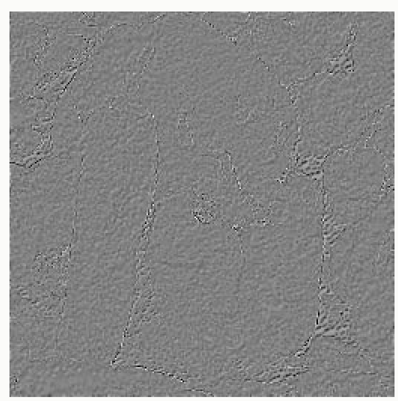
INVERSE HALFTONING MODEL

- Forward/inverse halftoning system blurs image and adds noise
- Model inverse halftoning
  - Compute unsharpened halftone
  - Inverse halftone; save filter parameters at each pixel
  - Filter original image using saved filters
- Typical correlation
  - Inverse halftone: $C_{RI} = 0.32$
  - Model inverse halftone: $C_{RI} = 0.01$



Inverse halftone

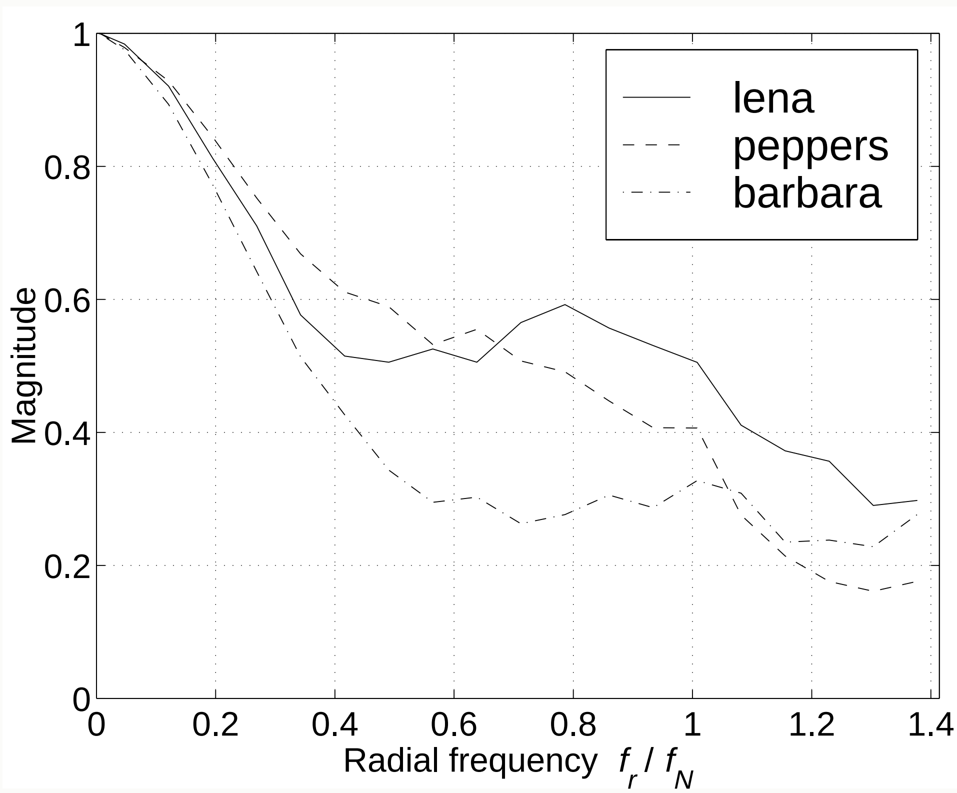
Modeled



Residual (×4)

INVERSE HALFTONE QUALITY

- Compute WSNR
- Compute effective transfer function
  - Divide FFT of model inverse halftone by FFT of original image
  - Radially average over annuli



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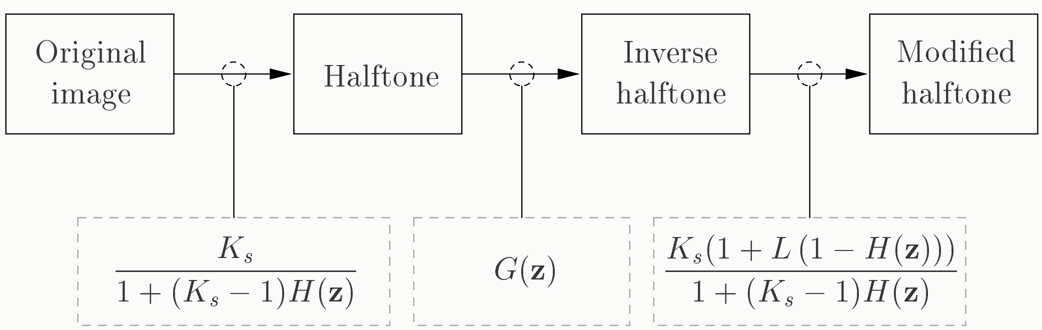
REHALFTONING

- Halftone conversion, manipulation
- Assume input and output are error diffused halftones
- Fixed lowpass inverse halftoning filter, compromise cut-off frequency
  - Noise leakage masked by halftoning
  - Blurring correctable by modified error diffusion
  - Computationally efficient

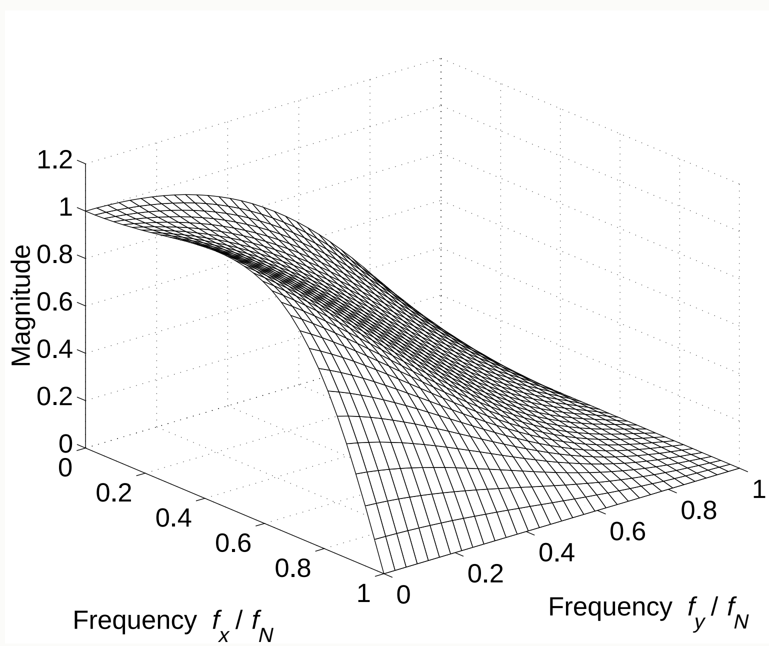


- Use linear gain model to design L for flat response
- Use approximation for digital frequency: $e^{j\omega} \approx 1 + j\omega - \omega^2/2$

REHALFTONING RESULTS

Original image

Rehalftone



Signal transfer function

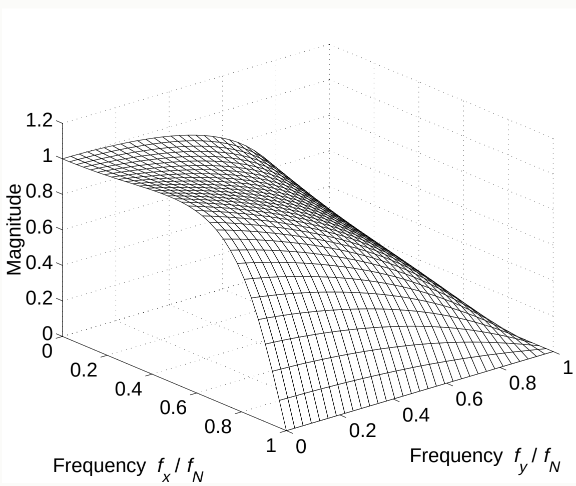
INTERPOLATION

- Image resizing
- Different methods (increasing cost)
  - Nearest neighbor
  - Bilinear
  - Bicubic, cubic splines, lowpass filtering
- Nearest neighbor, bilinear methods
  - Low computational cost
  - Artifacts masked by quantization noise in halftone
  - Blurring correctable by modified error diffusion
- Examine $\times 2$ interpolation; method applies to any scaling factor
- Design *L* for flat transfer function using linear gain model
- *L* constant for given interpolation scheme

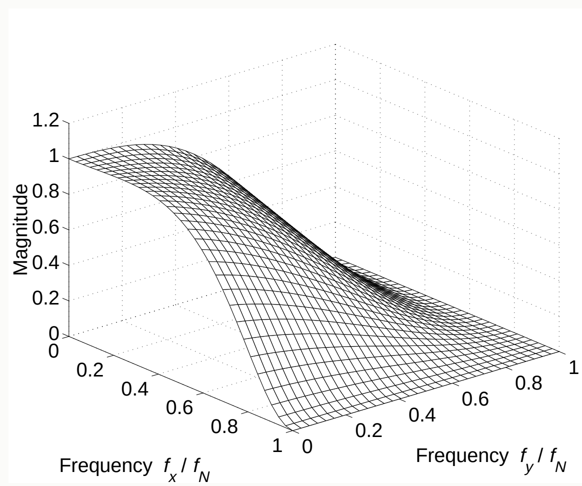
INTERPOLATION RESULTS

Nearest neighbor ×2

Bilinear ×2



Transfer function
L = –0.0105



Transfer function
L = 0.340

CONTRIBUTIONS

- Visual quality metrics for forward and inverse halftones
  - Restriction on correlation for accuracy of WSNR metric
- Linear gain model of error diffusion
  - Accuracy of model established
  - Tonality metric for artifacts
  - Link between filter gain and signal gain
- Inverse halftoning
  - New efficient method, suitable for hardware and embedded software
  - Model for inverse halftoning
  - Quality metrics for inverse halftones
- Rehalftoning and interpolation
  - Efficient algorithms
  - Verifies validity of linear gain model