Watermarking Printed Images*

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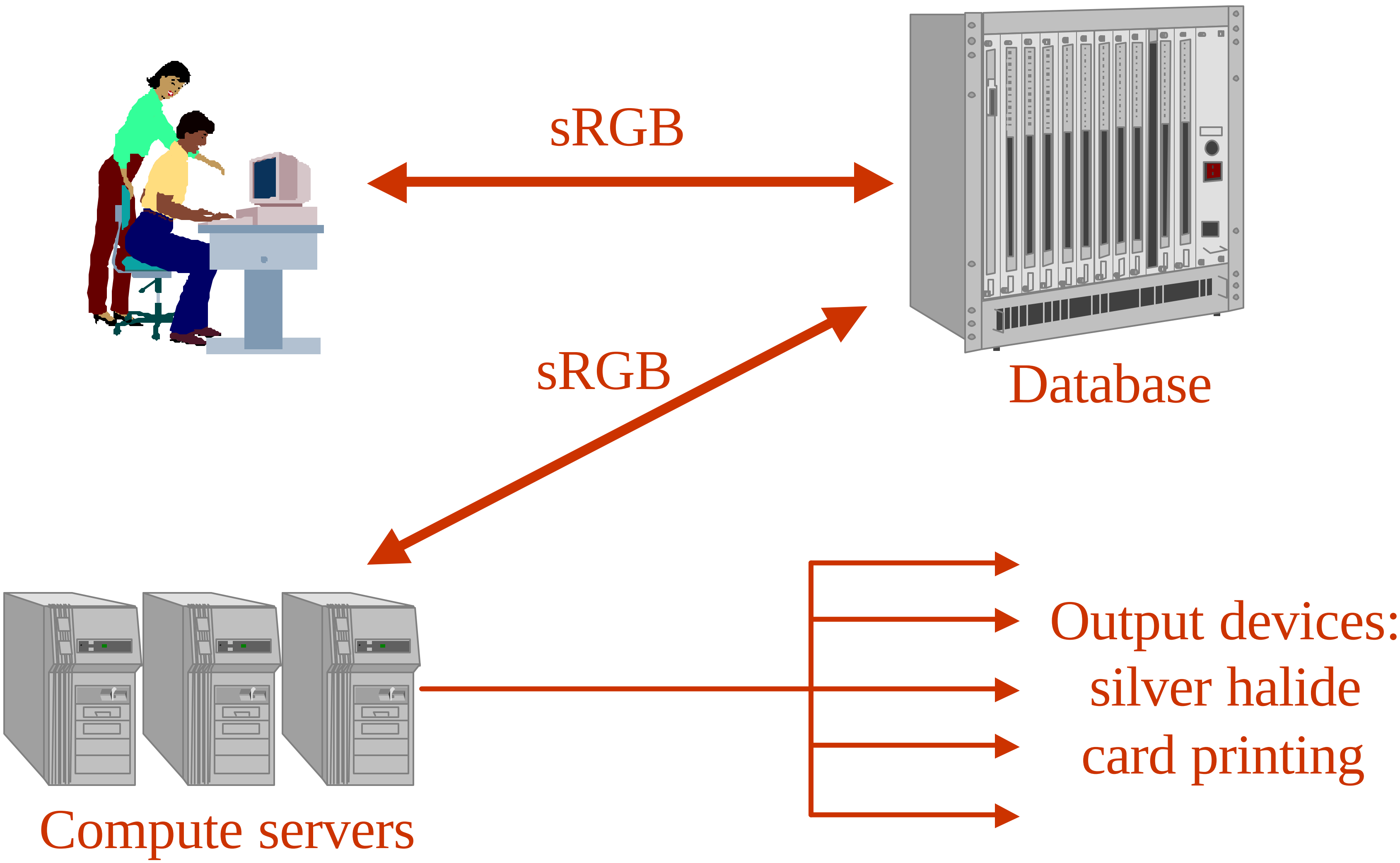
*Research supported by the Hewlett-Packard company

What is Shutterfly?

- Consumer Digital Printing Company:
  - Silver Halide prints
  - Greeting cards on card stock paper
  - Film developing and scanning
  - Online photo-editing
  - Web sharing
- Fulfillment partner for
  - Yahoo! Photos
  - Adobe Active Share
  - Best Buy

Shutterfly Printing Infrastructure



Acknowledgement

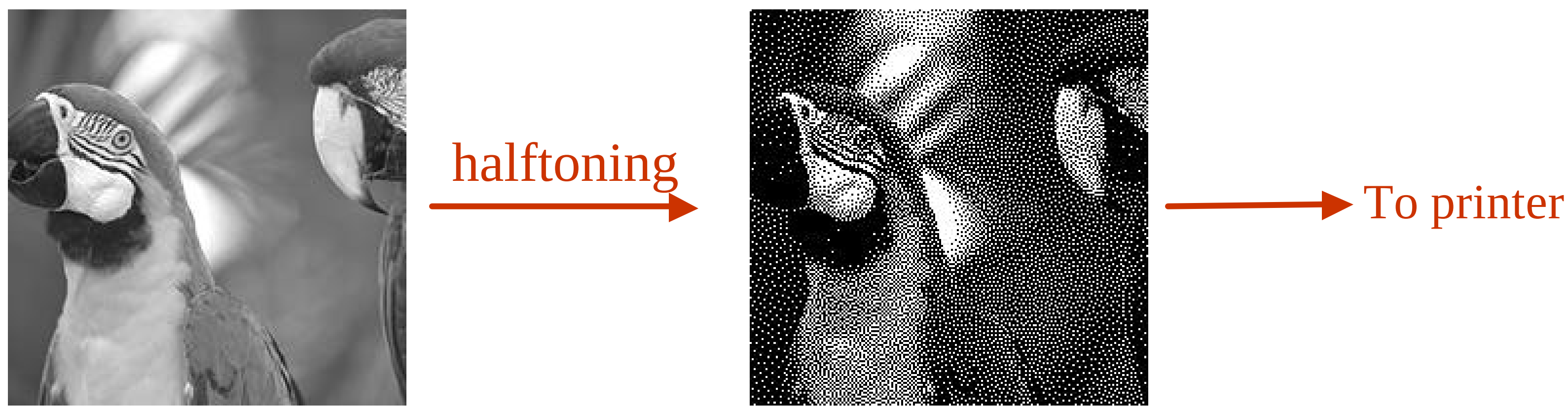
- Direct Binary Search basics taken from Jan P. Allebach's presentation at EI-2001
  - implicit in that is the work of numerous researchers at the Electronic Imaging Systems Laboratory at Purdue University
- The Hewlett-Packard company for supporting a significant portion of this research

Talk Overview

- Direct Binary Search (DBS) halftoning algorithm
  - Human Visual System (HVS) error metric
  - Efficient computation
  - Search Strategy
  - Printer Models
- Watermarking Printed Images
  - Spread Spectrum Watermarking (SSWM)
  - Block Based SSWM
  - Results

Common Printing Environment

- **Convert continuous-tone image into a bitmap, i.e. halftone the image**



Continuous-tone (MxN) Bitmap/halftone (MxN)

- **To a first degree of approximation, the human visual system acts as a low-pass filter**

Three categories of digital halftoning methods

- Point processes - screening
- Neighborhood processes - error diffusion
- Iterative processes - direct binary search (DBS)

DBS screen

Error diffusion

DBS

What is DBS?

- Cost minimization approach to halftoning
- Minimize a human visual system (HVS) based cost function between the continuous-tone image and the bitmap
- Provide a computationally feasible search heuristic

- **Direct Binary Search halftoning algorithm**
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Human Visual System Based Cost Function

$f[m,n]$ – continuous tone image $\quad f[m,n] \in [0,1]$

$g[m,n]$ – halftone/bitmap $\quad g[m,n] \in \{0,1\}$

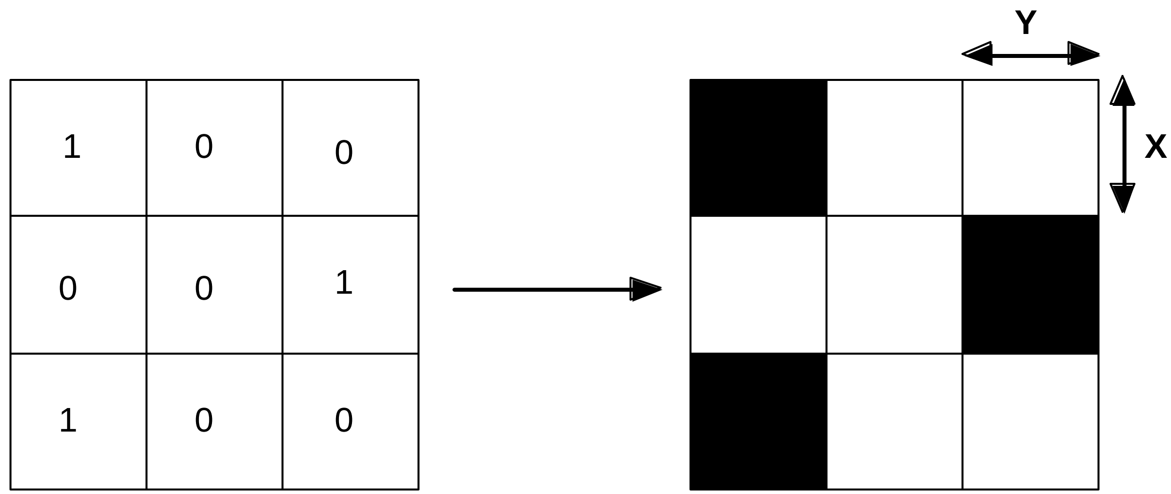
$p(x,y)$ – Printer dot profile function

$h(x,y)$ – Human Visual System PSF

$\tilde{f}(x,y)$ – Perceived continuous-tone image

$\tilde{g}(x,y)$ – Perceived halftone image

HVS Cost Function (cont.)



Bitmap g[m,n]

Ideal Printer Rendition

Dot profile function of an ideal printer: $p(x, y) = \text{rect}(\frac{x}{X}, \frac{y}{Y})$

$$g[m,n] = \begin{cases} 1 & \text{(max. absorptance)} \\ 0 & \text{(min. absorptance)} \end{cases}$$

Rendered image: $g(x,y) = \sum_{m} \sum_{n} g[m,n]\, p(x - mX, y - nX)$

HVS Cost Function (cont.)

Ideal rendition of the continuous-tone image:

$$f(x,y)=\sum_{m}\sum_{\text{n}} f[m,n]p(x-mX,y-nY)$$

where,

$$f[m,n]\in[0,1]$$

perceived continuous-tone image:

$$\tilde{f}(x,y)=f(x,y)**h(x,y)$$

similarly, perceived halftone image:

$$\tilde{g}(x,y)=g(x,y)**h(x,y)$$

HVS Cost Function (cont.)

Finally, perceived error image is given by:

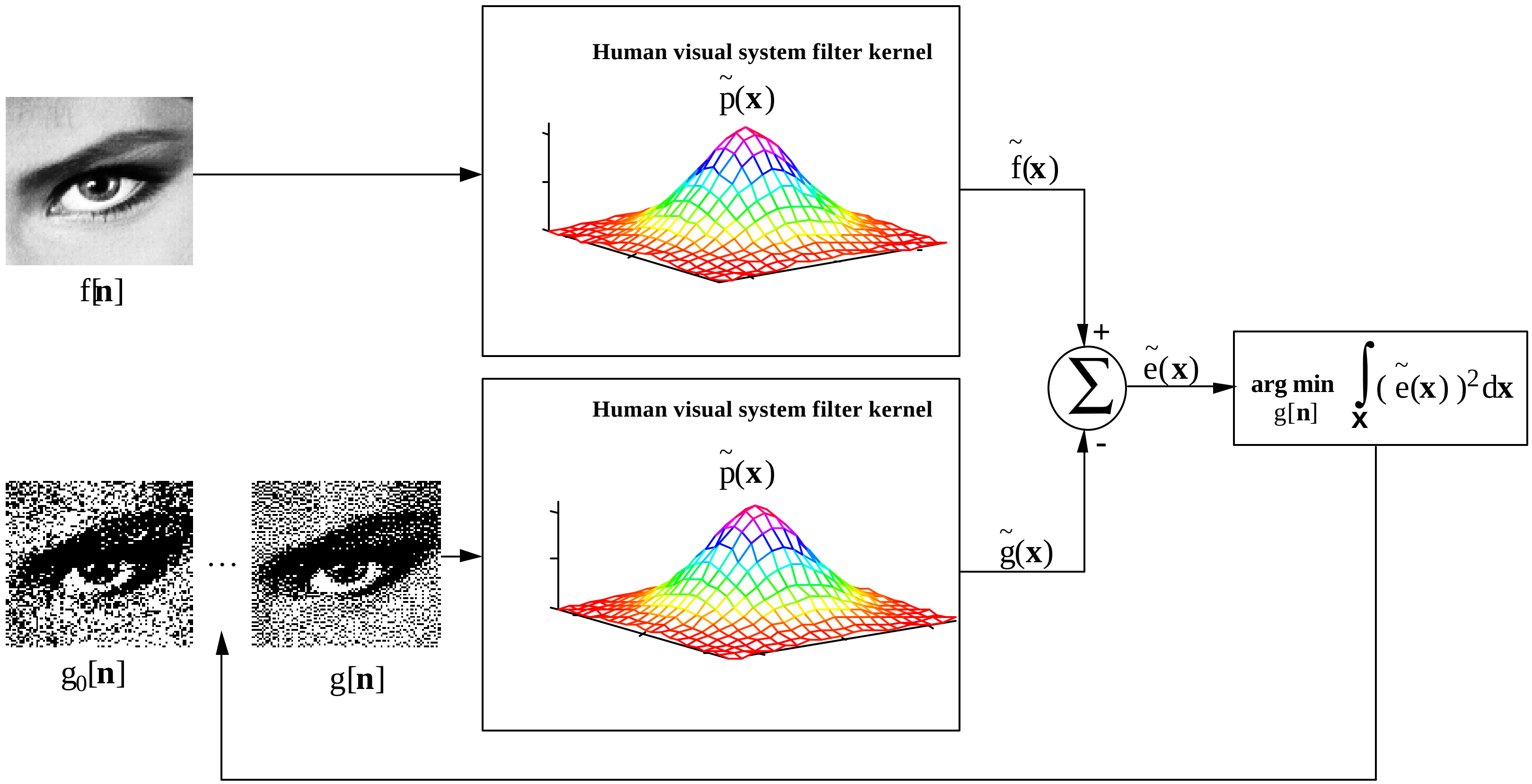
$$\tilde{e}(x,y) = \tilde{f}(x,y) - \tilde{g}(x,y)$$

Mean squared error:

$$e = < \tilde{e}(x,y), \tilde{e}(x,y) >$$

DBS searches for *g[m,n]* that minimizes ε

Direct binary search



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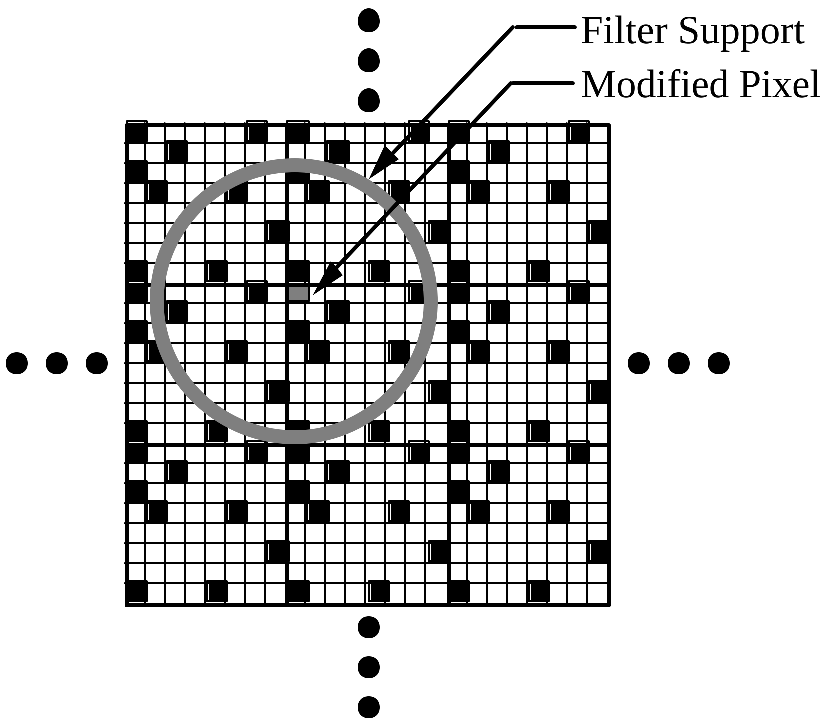
Computation

- **Direct computation of effect of a trial change requires** $O(P)$ **operations for filter containing** P **pixels.**



Efficient Computation

A candidate change:

$$g'[m,n] = g[m,n] + \sum_{l=1}^{L} a_l d[m - m_l, n - n_l] \qquad a_l = \pm 1$$

Can be shown that:

$$\Delta e = -2 \sum_{i=1}^{L} a_i \tilde{C}_{ep}[m_i, n_i] + \sum_{i=1}^{L} \sum_{j=1}^{L} a_i a_j \tilde{C}_{pp}[m_i - m_j, n_i - n_j]$$

where,

$$\tilde{C}_{pp}[m,n] = < \tilde{p}(x,y), \tilde{p}(x - mX, y - nY) >$$
$$\tilde{C}_{ep}[m,n] = < \tilde{e}(x,y), \tilde{p}(x - mX, y - nY) >$$

$$\tilde{p}(x,y) = p(x,y) ** h(x,y)$$

Accept a change when $\Delta e < 0$

Efficient Computation (cont.)

Once a change is accepted, need to update:

$$\tilde{C}'_{ep}[m,n] = \tilde{C}_{ep}[m,n] - \sum_{i=1}^{L} a_i \tilde{C}_{pp}[m - m_i, n - n_i]$$

O(P^2*)* operations

Why is this faster?

- $\Delta\varepsilon$ is computed very often
- As a percentage very few candidate changes are accepted and therefore comparatively few updates are required.

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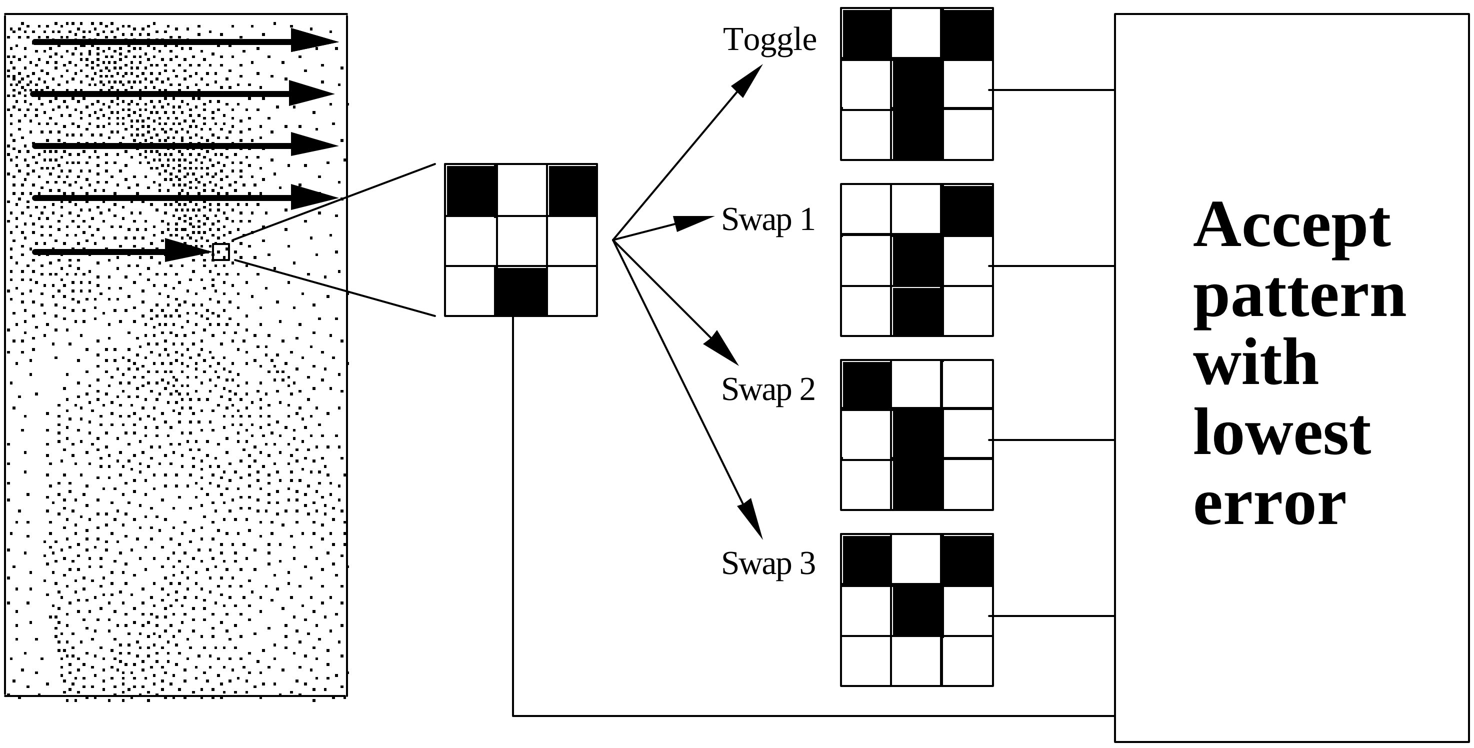
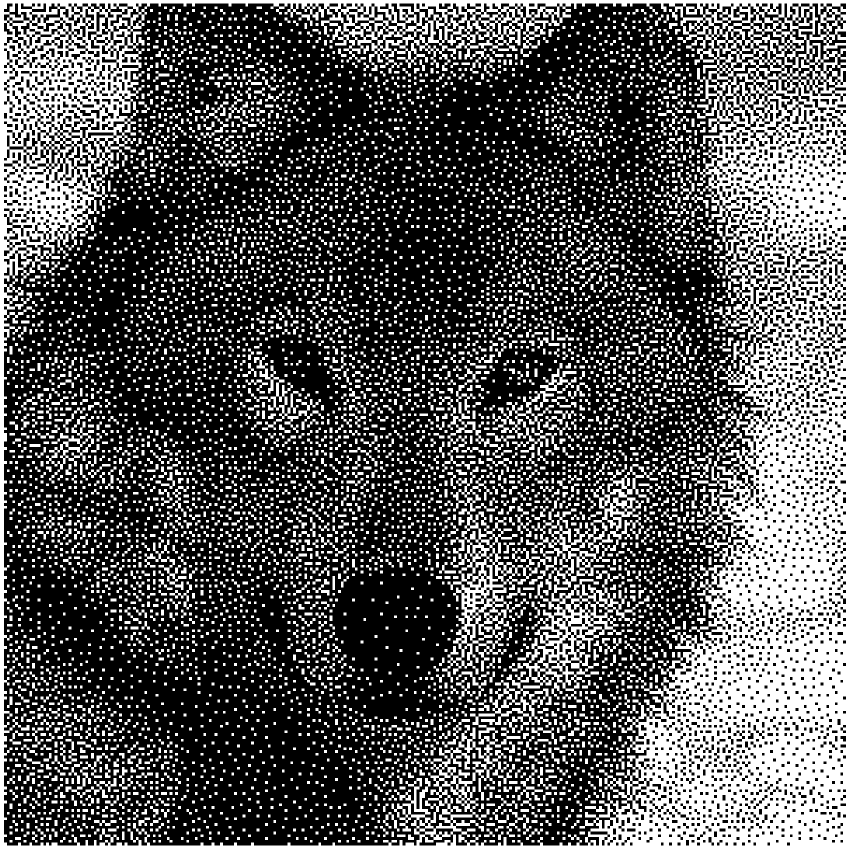
The search heuristic



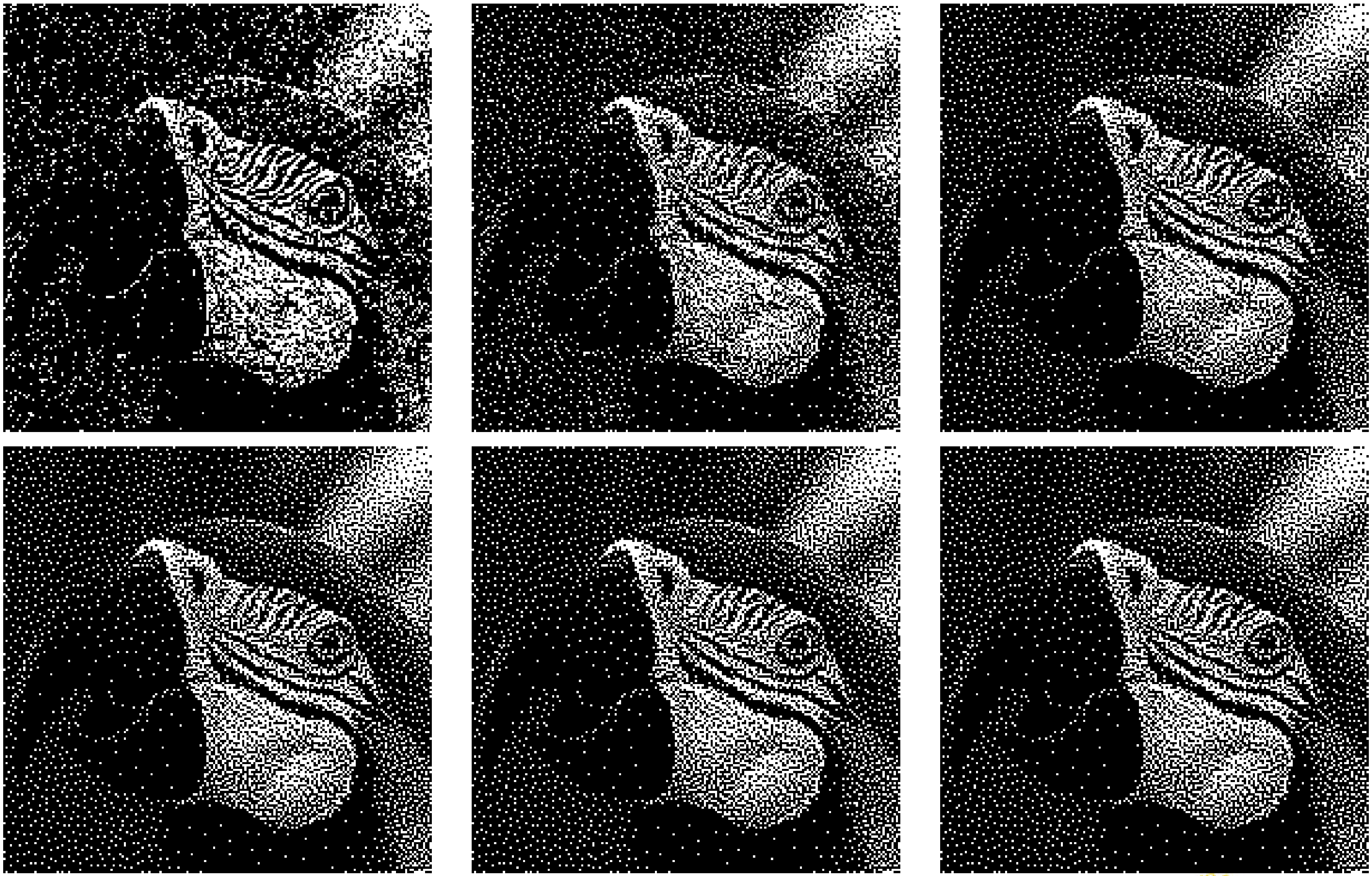
Swaps vs. toggles

Toggle only



Swap and toggle

DBS convergence: 0, 1, 2, 4, 6, and 8 iterations



Why DBS?

- Not practical for most desktop publishing applications.

But

- Provide basis for design of computationally simpler strategies.
- Serve as benchmark for judging halftone image quality.

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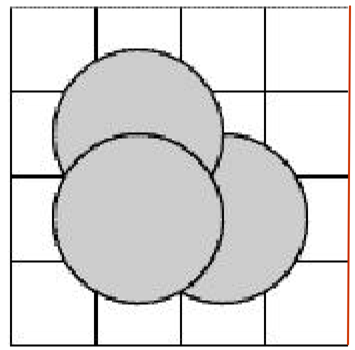
Accounting for non-ideal printers

- Tone-reproduction curves
  - pre-process the continuous-tone image
- Model based techniques
- Measurement based techniques

Equivalent Grayscale Image

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

Bit Map



Detailed model for rendered halftone

0.03	0.33	0.03	0.00
0.33	1.00	0.56	0.03
0.33	1.00	1.00	0.33
0.03	0.33	0.33	0.03

Equivalent gray values

- **Can be used with wide range of detailed models for rendered halftone**
  - **hard circular dot model (Pappas and Neuhoff, and others)**
  - **tabular model (Pappas, Neuhoff, Dong, 1993)**

Printer model based DBS

- Replace binary digital halftone $g(x,y)$ by equivalent grayscale image $\hat{g}(x,y)$
- Perceived error with printer model

$$\tilde{e}(x,y) = h(x,y) ** \left(\hat{g}(x,y) - f(x,y)\right)$$

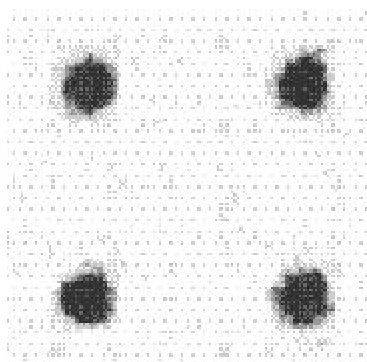
- Efficient evaluation of effect of trial changes is still possible, but with greater computational complexity

Stochastic DBS

- **Lin and Wiseman's non-overlapping grain model (Flohr)**
- **Overlapping grain model (Flohr)**
- **Tabular model (Baqai)**

Minimum Variance Pattern

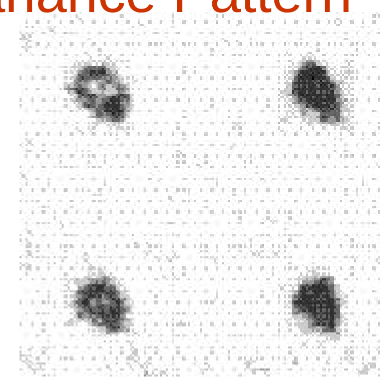
0	1	1
1	1	1
0	1	1



Avg. = 0.76, Std. Dev. = 0.089

Maximum Variance Pattern

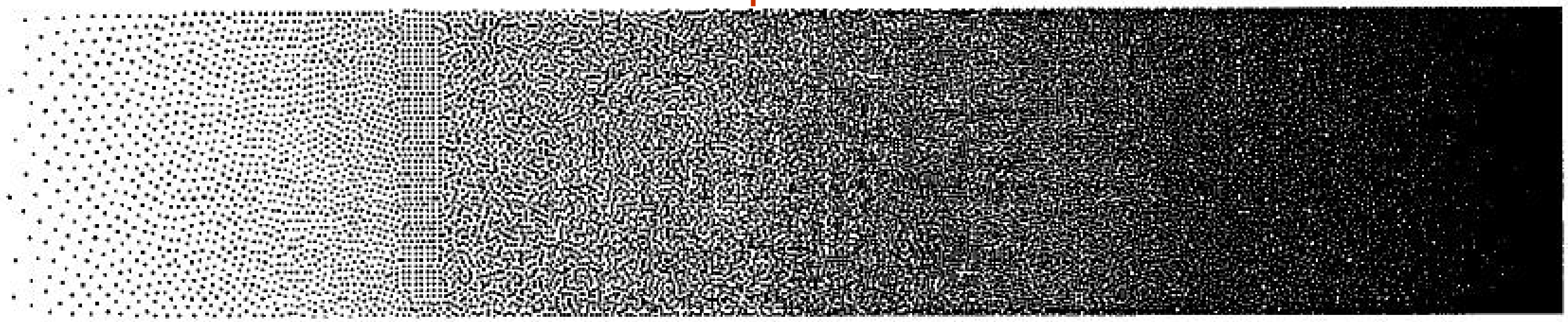
0	1	0
1	1	1
0	0	1



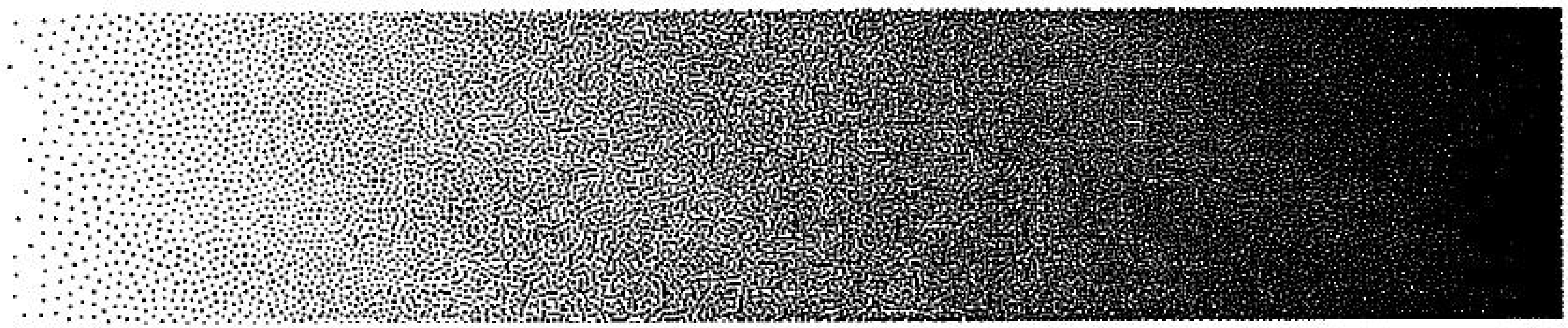
Avg. = 0.58, Std. Dev. = 0.480

Simulated printer output (Baqai)

DBS with no printer model

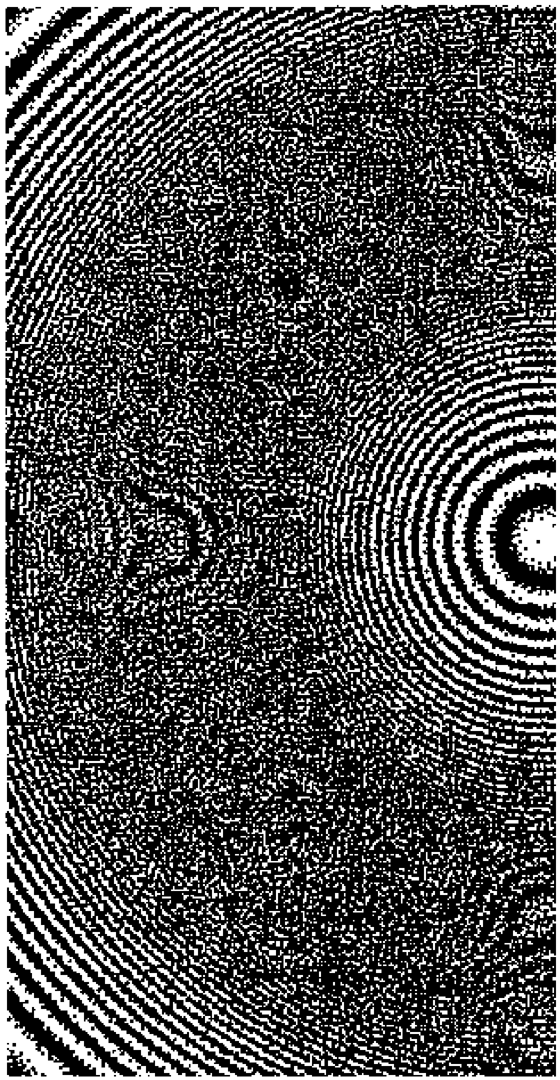


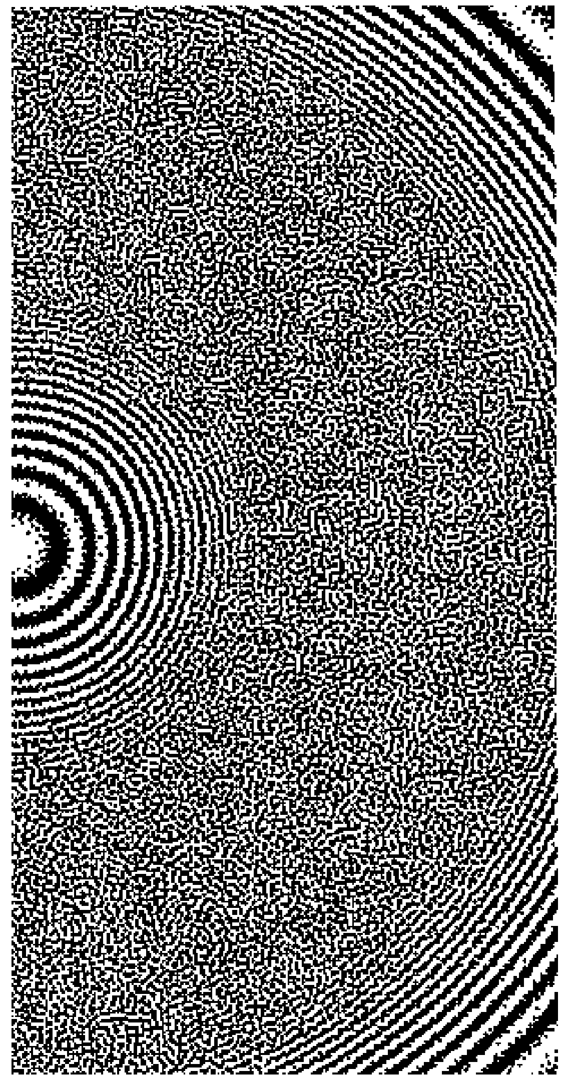
DBS with hard circular dot model



Simulated printer output (cont.)

DBS with no printer model





DBS with hard circular dot model

Printer model-based DBS

- EP process characterization model (Kacker and Camis)
  - analytical model for exposure step
  - empirical model for development and fusing
- Tabular model for color printer (Flohr, Agar)
  - Error based on Yc_xc_z color space
  - uses Wang's offset centering method
  - Can directly control CMYK percentages

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Halftoning and Watermarking

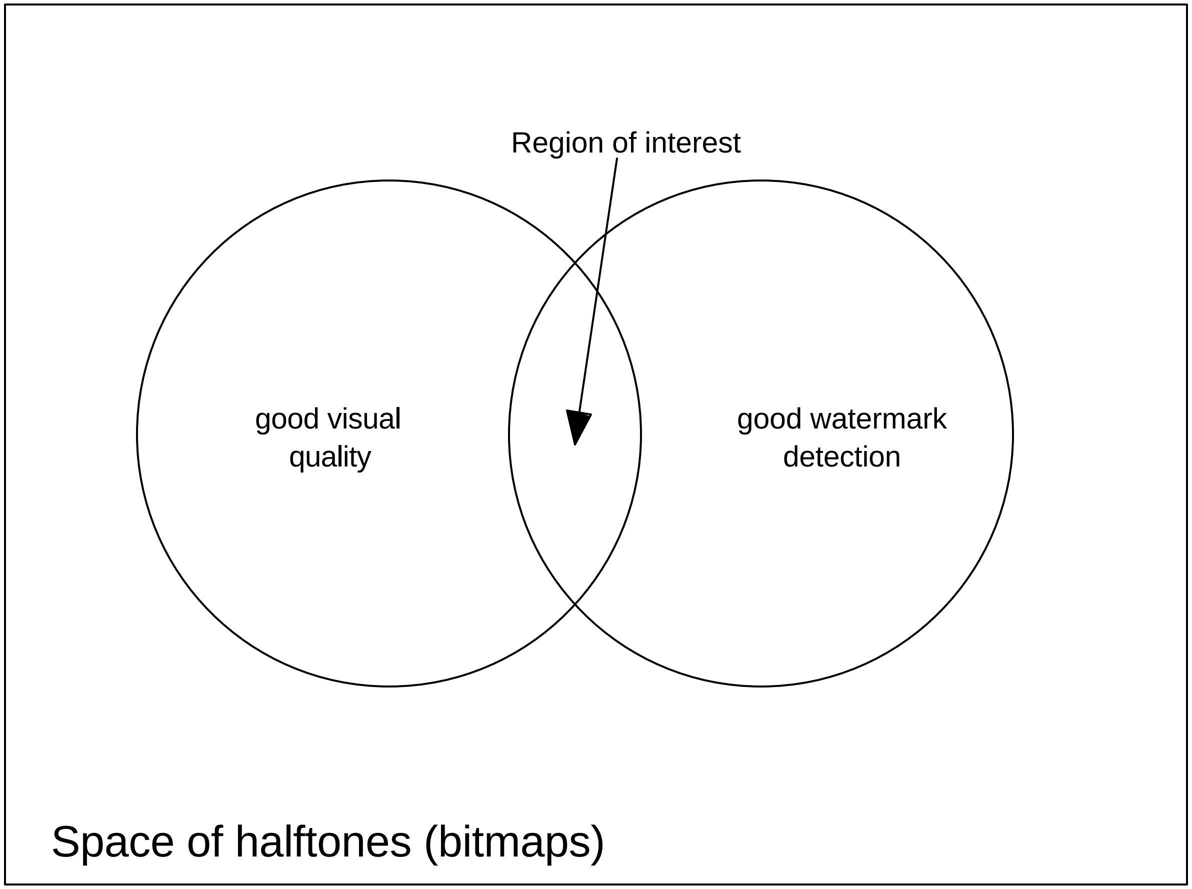


Image size: MxN, 2^{MxN} possible halftones

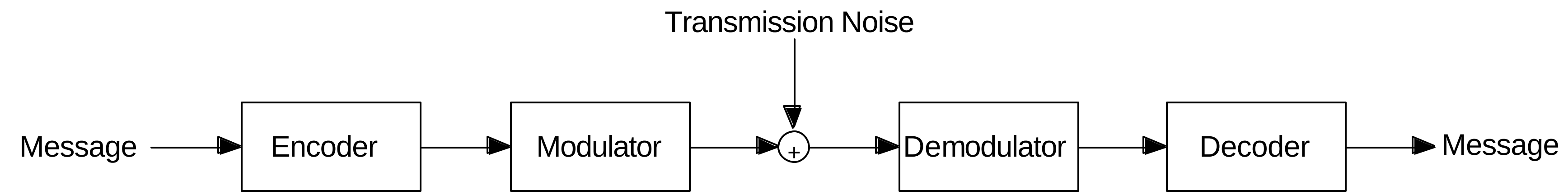
Our Focus

- Watermarking for hardcopy imaging applications
  - » Detection of aperiodic micro-screens (Z.Baharav & D.Shaked, HP Labs, Israel)
  - » Screen modifications to reveal watermarks (K. Knox and Shen-Ge Wang, Xerox).
- Detect watermark from scanned image.
- Explicitly take into account the printing process.
- Original image is available.

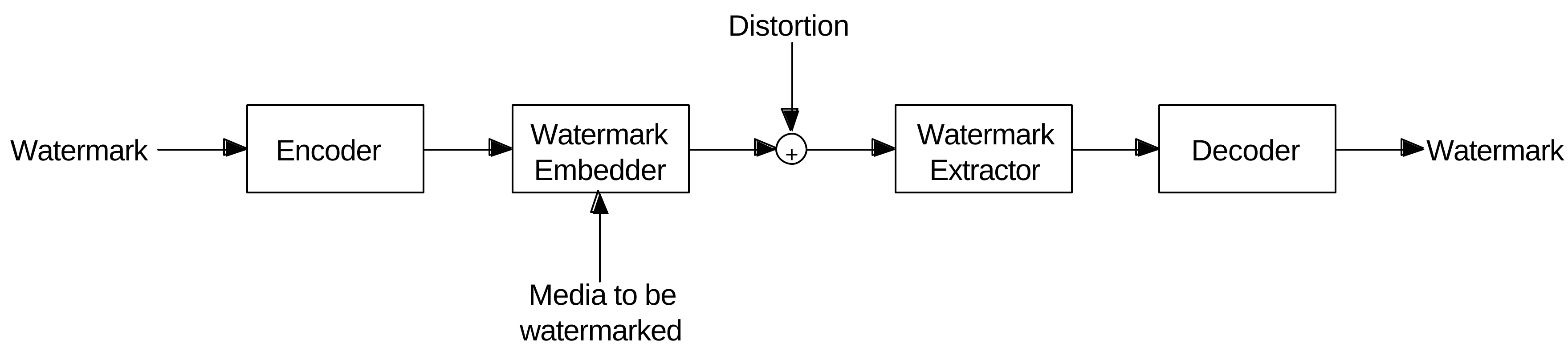
Requirements: Two Metrics and a Search Strategy

- **Metrics:**
  - **A visual metric to determine good visual quality region.**
  - **A metric to determine good watermark detection.**
- **Search strategy to traverse the space of 2^{MxN} halftones.**

Watermarking as a Communications Problem*



Classical Communications Channel



Watermarking as Communications

*Cox *et al*, "Watermarking as Communications with Side Information," *Proceedings of the IEEE*, vol.87, no.7, July 1999.

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Spread Spectrum Watermarking

Spread Spectrum:Means of communications in which the signal occupies a bandwidth in excess of the minimum necessary.

- **Anti-jamming**
  - **Malicious attempts to remove watermark**
- **Anti-interference**
  - **Robust to distortions (comp., filtering etc.)**
- **Low probability of intercept**
  - **Inability to completely decode watermark**

Hardcopy renditions result in highly non-linear forms of distortions. Hence SS watermarking is suitable.

Spread Spectrum Watermarking*

Original Image $f[i,j] \rightarrow \boxed{\text{DCT}} \rightarrow F[k,l]$

Watermark Embedder

$$F'[k,l] = \begin{cases} F[k,l](1+\alpha W[k,l]) & \text{if } |F[k,l]| > \mathbf{T} \\ F[k,l] & \text{otherwise} \end{cases}$$

α - strength of watermark

$W[k,l]$ - watermark sequence ~ N(0,1) i.i.d.

$F'[k,l] \rightarrow \boxed{\text{IDCT}} \rightarrow f'[i,j]$ Watermarked Image

*Cox *et al*, "Secure Spread Spectrum Watermarking for Multimedia," *IEEE Tran. Image Proc.*, vol.6, no.12, Dec. 1997.

Watermark Extractor and Correlation Detector

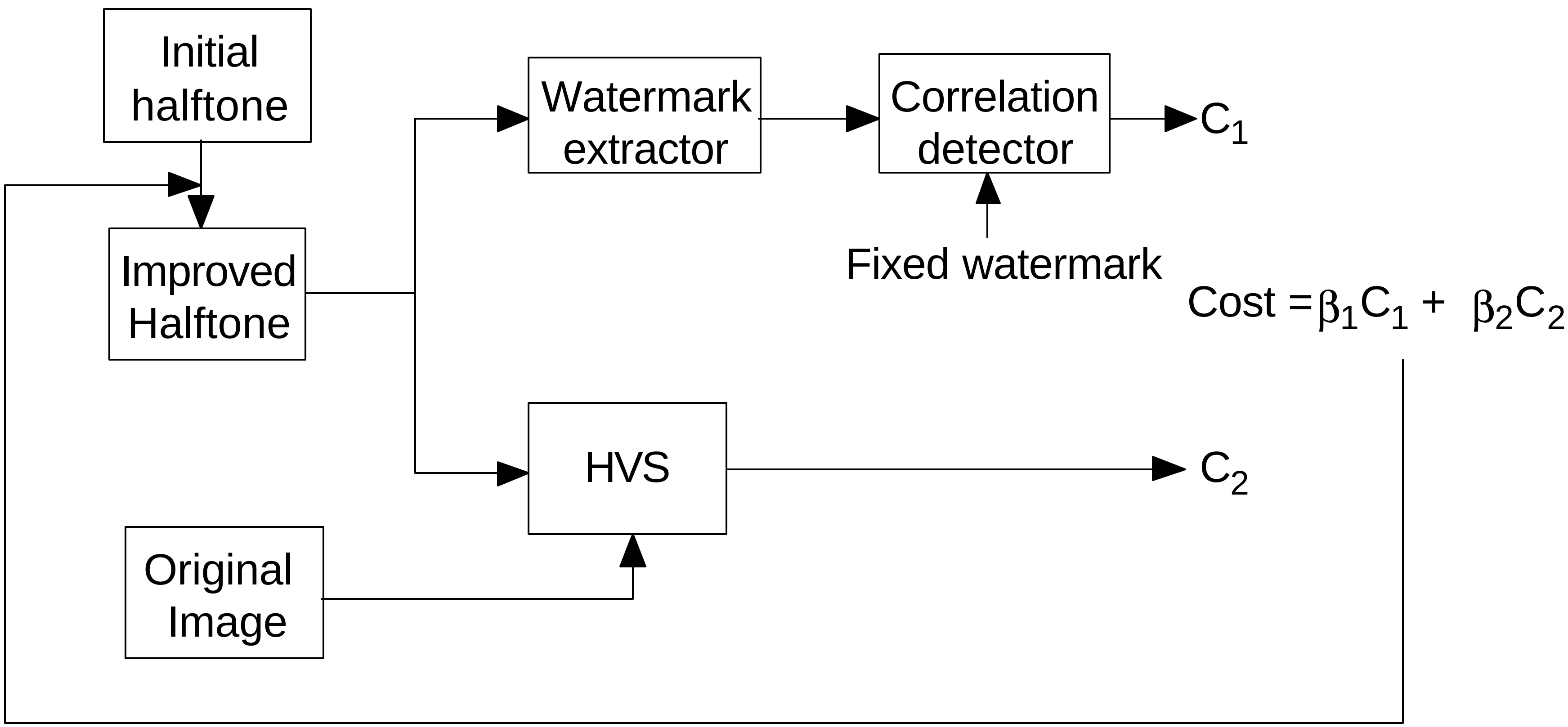
$$f'[i,j] \longrightarrow \boxed{\text{distortion/ manipulation}} \longrightarrow f''[i,j]$$

$$W^*[k,l] = \frac{\left(\dfrac{F''[k,l]}{F[k,l]} - 1\right)}{\alpha}$$

$$\gamma = \frac{\langle W^*, W \rangle}{\left(\langle W^*, W^* \rangle\right)^{1/2}}$$

Higher γ, more robust to further degradations.
Typically γ greater than 6.0 is considered a positive detection.

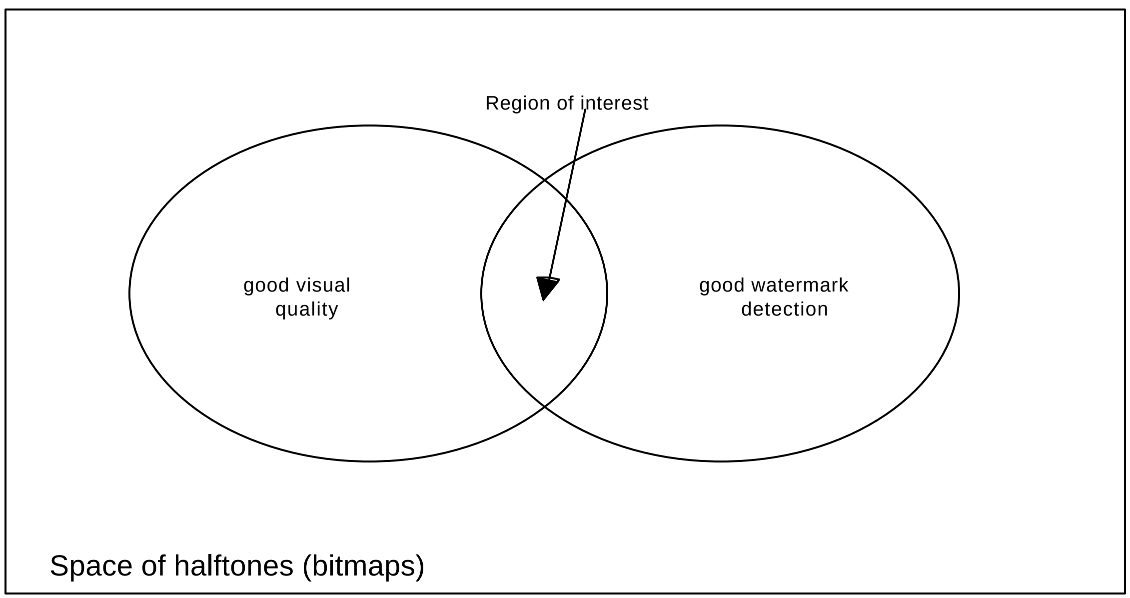
Joint Halftoning and Watermarking



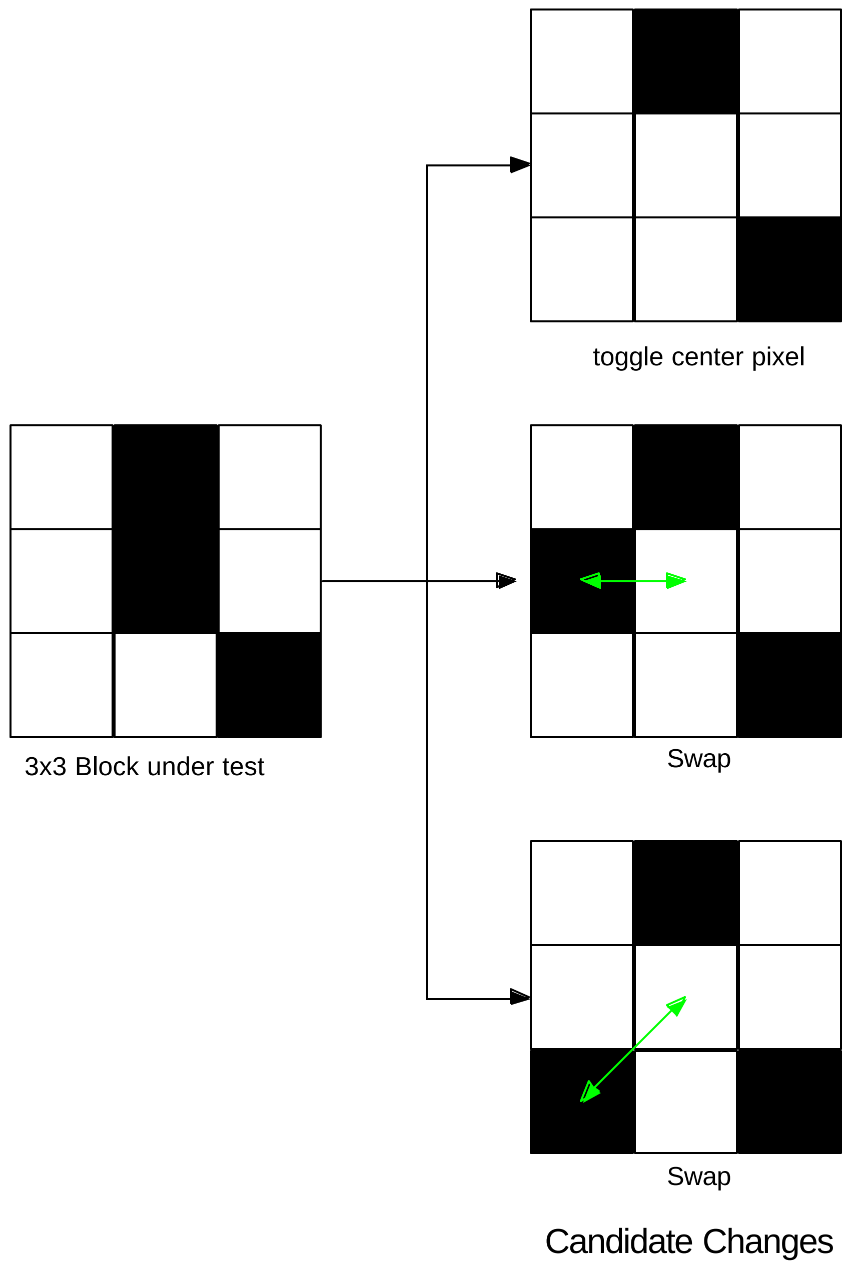
Next look at search strategy.

Initial Halftone

This initial halftone has both 'reasonable' image quality and 'reasonable' watermark detection.



Search Strategy



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Block Based Watermarking

Take P×Q length DCTs

Original Image $f[i,j] \rightarrow$ [PxQ DCT] $\rightarrow F[k,l]$

Watermark Embedder

$$F'[k,l] = \begin{cases} F[k,l](1+\alpha W[k,l]) & \text{if } |F[k,l]| > \mathbf{T} \\ F[k,l] & \text{otherwise} \end{cases}$$

$W[k,l]$ - watermark sequence ~ N(0,1) i.i.d

$F'[k,l] \rightarrow$ [PxQ IDCT] $\rightarrow f'[i,j]$ Watermarked Image

Discussion - Block Based SSWM

- **Larger the DCT size, greater the robustness to registration errors.**
- **Candidate change affects DCT coefficients only in a PxQ block.**
- **Can store DCT kernel for small PxQ.**

$$F[k,l] = \Sigma\Sigma f[m,n] F[m,n;k,l]$$

F - can be stored as a LUT

Experimental results show that P=Q=32 provides a good compromise.

Algorithm Overview

- Minimize joint HVS error and watermark detection cost function
- Search space of 2^{MxN} halftones
  - Initial halftone
  - Swaps and toggles search strategy
  - Block based SSWM

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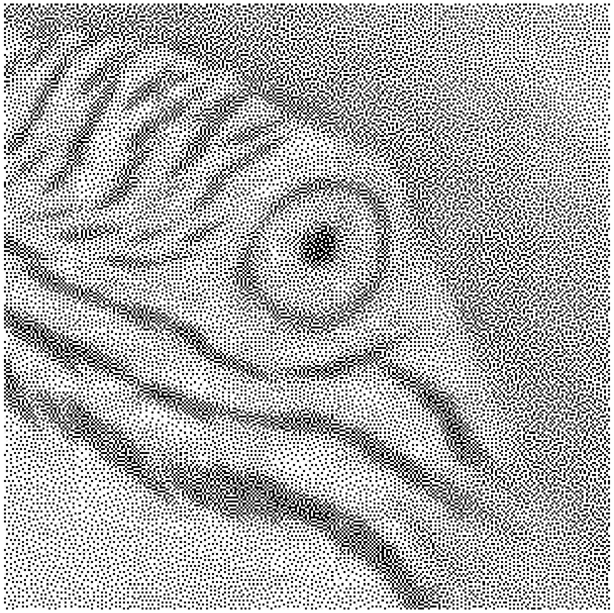
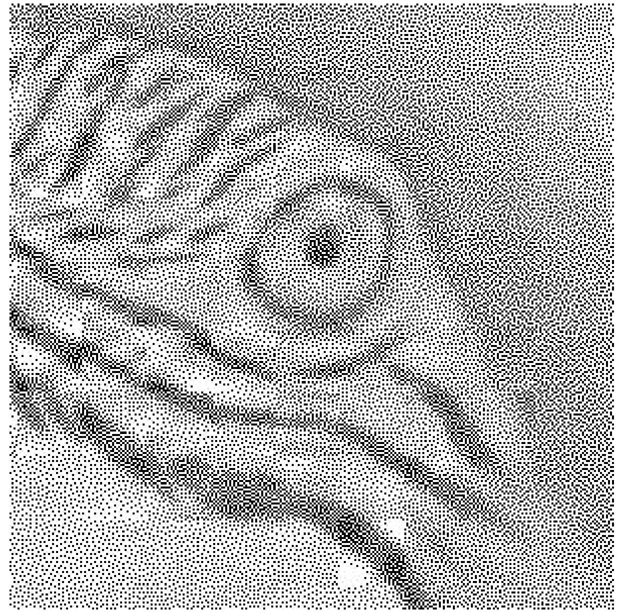
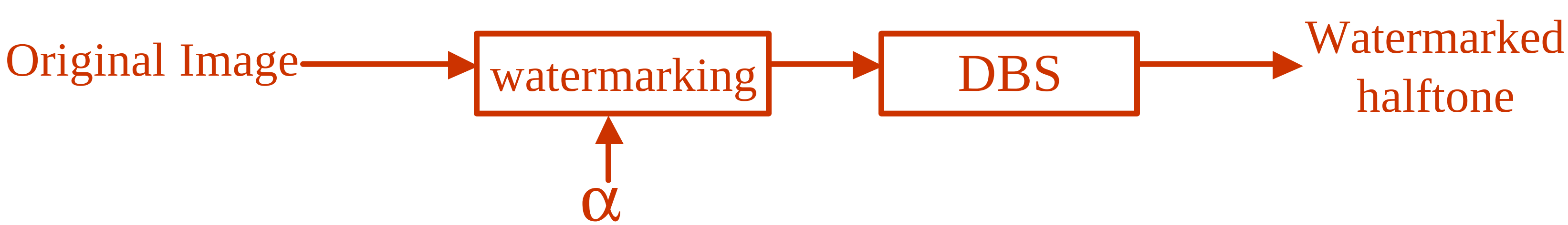
Results

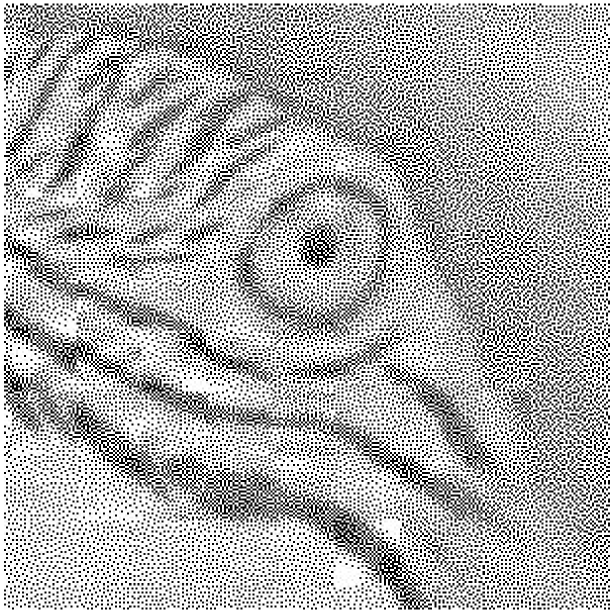


α=0.3

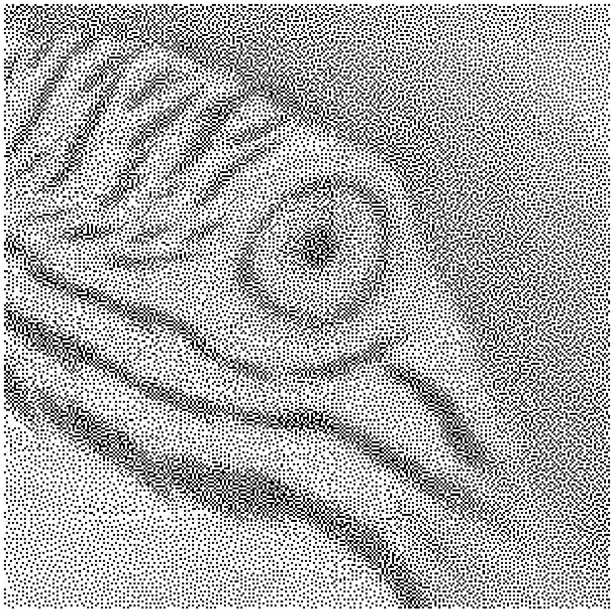


α=0.48

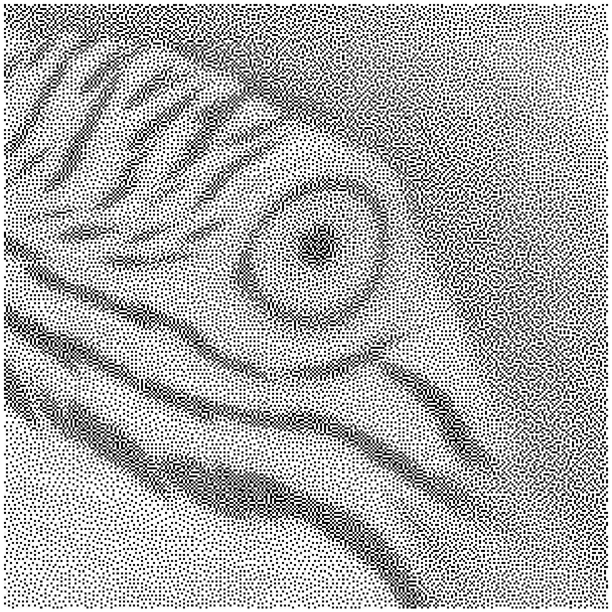




α=0.48 (initial halftone)



Optimized



DBS Halftone

Results

- **Images printed at 600dpi, scanned at 300dpi using a HP ScanJet 6100C. Used pixel replication to get full resolution image.**

	Bitmap	Scanned	Artifacts
1) Const. α=0.30	68.09	13.84	No
2) Const α=0.48	93.95	31.03	Yes
3) Optimal Halftone	95.06	26.33	No

Correlation detector output (γ) for bitmap and scanned images

- Image Size: 2048x3072
  18,819 coefficients (0.3%) watermarked.
- 6hrs to jointly optimize visual quality and watermark detection.

Conclusions

- Algorithm works well for images scanned using a flat bed scanner.
- Joint optimization of watermark detector output and halftone quality produces images comparable to regular DBS.
- Watermark encoding stage is computationally expensive; best used in applications where encoder complexity is not an issue.
- Demonstrated the use of general framework for jointly halftoning and watermarking.

Some applications

- **Ordering re-prints**
  - **Need about 60bits+/image**
  - **Needs to work on 99.9% of the images**
    - » **at least identify subset on which it works (3MegaPix+, image content etc.)**
- **Improving mass printing workflow**
  - **Need about 10bits/image**
  - **Needs to work on <u>every</u> image**
    - » **at least clearly identify failure apriori**

•Computationally inexpensive to embed

•Robust to typical errors in printing/scanning **<u>but</u>** need not be robust to all possible distortions.

•Simple and fast detection

DBS One-Stop-Shop

Jan P. Allebach, “DBS: Retrospective and Future Directions,” in *Proc. of the 2001 SPIE Electronic Imaging Conf.*, pp358-376, San Jose, CA, SPIE Vol. 4300.