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Contrast-aware Halftoning

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Abstract

This paper proposes two variants of a simple but efficient algorithm for structure-preserving halftoning. Our algorithm extends Floyd-Steinberg error diffusion; the goal of our extension is not only to produce good tone similarity but also to preserve structure and especially contrast, motivated by our intuition that human perception is sensitive to contrast. By enhancing contrast we attempt to preserve and enhance structure also.

Our basic algorithm employs an adaptive, contrast-aware mask. To enhance contrast, darker pixels should be more likely to be chosen as black pixels while lighter pixels should be more likely to be set as white. Therefore, when the positive error is diffused to nearby pixels in a mask, the dark pixels absorb less error and the light pixels absorb more. Conversely, negative error is distributed preferentially to dark pixels. We also propose using a mask with values that drop off steeply from the centre, intended to promote good spatial distribution. It is a very fast method whose speed mainly depends on the size of the mask. But this method suffers from distracting patterns.

We then propose a variant on the basic idea which overcomes the first algorithm's shortcomings while maintaining its advantages through a priority-aware scheme. Rather than proceeding in random or raster order, we sort the image first; each pixel is assigned a priority based on its up-to-date distance to black or to white, and pixels with extreme intensities are processed earlier. Since we use the same mask strategy as before, we promote good spatial distribution and high contrast.

We use tone similarity, structure similarity, and contrast similarity to validate our algorithm. Comparisons with recent structure-aware algorithms show that our method gives better results without sacrificing speed.

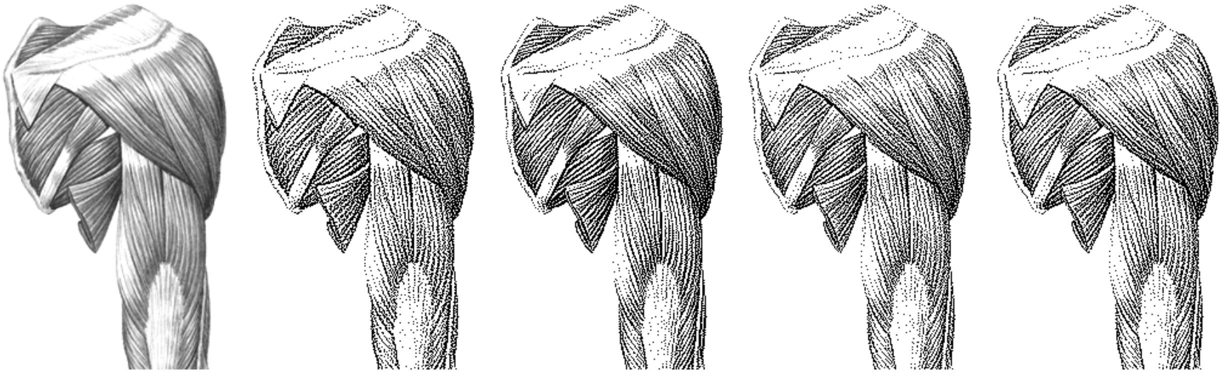
Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Picture/Image Generation—Digitizing and scanning

1. Introduction

Halftoning refers to converting a continuous-tone image into a pattern of black and white dots [Uli87]. The key factors for the quality of halftoning are the precise preservation of both tone and structure from the original image, and the absence of spurious patterns. How to satisfy and balance those factors has inspired a lot of modern halftoning algorithms.

Halftoning methods are usually classified as three groups: point processes such as dithering methods [BAY73, Uli87], neighborhood processes such as error diffusion [FS74, VG91, EK91, Ost01, ZF03, KRA06, CAO09], and iterative methods [AA92, BTA03, PQW*08]. Iterative methods, due to their computational expense, did not attract many researchers for a long time. However, recently, Pang et al. [PQW*08] presented structure-aware halftoning (SAH), which uses an iterative policy to optimize an objective function, obtaining impressive structure preservation. Even more recently, Chang et al. [CAO09] proposed structure-aware error diffusion (SAED): a non-iterative method that addresses Pang et al.'s problem of low speed. Unfortunately, the structure preservation from SAED is lower than SAH. Therefore, we propose our more simple and efficient method which gives higher structure quality. Some sample results are shown in Figure 1.

We are motivated by the observation that contrast [Bad88, HW97, Reg00] is an important consideration in human perception of an image. Our contrast-aware methods are intended to extend classic error diffusion with considerations of contrast preservation. We propose dynamically calculating the priority of every pixel as we proceed through the halftoning process, which further improves our contrast-aware scheme. The notion of a dynamic importance map



(a) The original image (b) SAH [PQW*08] (c) SAED [CAO09] (d) Our basic method (e) Our variant method

Figure 1: Illustration "arm". Image resolution is 200 by 307.

has been previously used in non-photorealistic rendering [Her98] but to our knowledge has not been applied to halftoning. We demonstrate superior structure preservation to both SAH [PQW*08] and SAED [CAO09] with speed competitive with SAED.

In Section 2 we discuss previous research and present our algorithms in Section 3. In Section 4 we give some sample images and report quality measurements comparing our results with those of previous methods. We conclude our paper in Section 5 and identify potential future work.

2. Previous Work

Early halftoning techniques were focused on the goal of tone matching. Dithering methods such as ordered dithering [BAY73] represent the desired intensity with some defined pattern. Regular patterns and visual artifacts are the main problem for this group of methods.

The well-known Floyd-Steinberg error diffusion (FSED) technique [FS74] was developed to circumvent those problems. The intensity difference between the original image and the approximated intensity (black or white in monochrome halftoning) – the error – is distributed to the neighboring pixels, which encourages smoothness. Most of modern halftoning methods cannot compete with error diffusion in tone reproduction. Following Floyd and Steinberg's idea, a great deal of work has been done in error diffusion [VG91, EK91, Ost01, ZF03, KRA06, CAO09]. Spurious patterns and lack of structure preservation are two big drawbacks for methods of this type. A well-accepted solution to visual artifacts is to enforce blue noise properties into halfoning [MP91, Ost01, BTA03, ZF03, KCODL06]. Ostromoukhov's method [Ost01] is a typical method for generating blue noise property by using an off-line minimization process for distributing coefficients over different intensity levels. But Ostromoukhov's method still does not attempt to retain structure, thus loses fine texture details.

Structure-aware methods are a recent trend in halftoning. Historically, image structure has been promoted by edge enhancement. Eschbach and Knox [EK91] employ an image-dependent threshold process to increase or decrease edge enhancement for their error diffusion method. However it fails on weak edges. Kwak et al. [KRA06] proposed an edge enhancement method based on the human visual system (HVS). It turns out the quality of results from edge enhancement is not pleasing. In 2008, Pang et al. [PQW*08] applied an optimization process to minimize an objective function balancing tonal control and structural adjustment (the SAH algorithm); in 2009, Chang et al. [CAO09] use a direct process for faster structure-preserving halftoning (called SAED). Both of their research can be treated as the state of art because the results from their methods are excellent. However, SAH is computationally expensive, which makes it difficult to use in practice; SAED does not achieve the same high level of structure similarity as SAH.

Contrast is a topic often neglected, though not inevitably. Li et al. [Li06] propose an edge-directed error diffusion method to preserve edges and contrast. In this method, diffusion halts at boundary edges; further, the algorithm's parameters are adaptively modified based on a binary edge image. However, this method suffers from artifacts similar to FSED. SAED [CAO09] uses contrast as a perceptual parameter in their calibration step. Marcu and Abe [MA96] gave a halftoning variant where pixels are visited in intensity order, but without much discussion and without dynamic updates to the order. Their method can be seen as a precursor to ours.

3. Contrast-Aware Halftoning Algorithm

Traditional Floyd-Steinberg error diffusion [FS74] has very good tone matching. In order to take full advantage of its graceful tone matching property, the methods we describe here are based on classic error diffusion; our innovation is to distribute error through contrast-aware weights within a normalized mask. A variant method of our basic contrast-aware method improves fine texture details, based on a flexible dynamic priority scheme.

3.1. Basic Algorithm

The idea behind our contrast-sensitive method is simple. Local contrast in monochrome halftoning is derived from the clustering of black pixels in a white area. If we observe a structure well-preserved by halfoning, it means that the black pixels are arranged to fall along the edges gracefully. The local contrast will be promoted if we use more black pixels in the dark side and fewer black pixels on the light side; doing this enhances texture edges as well. This observation is at the core of our algorithm.

Our algorithm proceeds pixel by pixel. The first step is to determine which color (black or white) should be chosen for this pixel. If the input pixel is closer to black in intensity value, black is chosen; otherwise, white is chosen. Next, the algorithm calculates the error between the original intensity and the chosen intensity (0 or 255) and the error is distributed to neighboring pixels based on our contrast-aware mask. As the algorithm progresses, we want to maintain the initial tendency that darker pixels should be more likely to be set to black while lighter pixels should be more likely to be set to white. A positive error, resulting from a dark pixel set to black, means the surrounding area should be lightened; a negative error, from a light pixel set to white, means the area is too light already and the neighborhood should be darkened. Our policy is that when positive error is diffused to nearby pixels, the darker pixels absorb less error and the light pixels absorb more: this biases the result such that pixels which were already lighter than their neighbors become even lighter, while darker pixels remain dark. Conversely, negative error is distributed preferentially to dark pixels, making them even darker.

The error is distributed within a circular mask centred on the pixel. Boundary pixels have fewer image pixels beneath the mask. Weights w_{st} are calculated, and then normalized weights $\hat{w}_{st}$ such that the sum of all $\hat{w}_{st}$ is unity. Error is distributed to each pixel in proportion to its $\hat{w}_{st}$. The weights w_{st} are computed as follows:

$$\text{if } error > 0, w_{st} = \frac{I_{st}}{(r_{st})^k} \tag{1}$$

$$\text{else, } w_{st} = \frac{(255 - I_{st})}{(r_{st})^k} \tag{2}$$

In the preceding, I_{st} is the intensity of pixel s,t beneath the mask, r_{st} is the distance of pixel s,t from the mask centre, and k is a parameter. We have intensity values ranging from 0 to 255. We produced our best results for balancing quality and speed with $k = 2.6$ and a 7 by 7 mask.

The normalized weights are computed by dividing by the sum of weights for all pixels within the mask region that were not previously set to their final values; such pixels are indicated as *done*:

$$W_{total} = \sum_{(s,t) \in neighbors \setminus done} w_{st} \tag{3}$$

$$\hat{w}_{st} = \frac{w_{st}}{W_{total}} \tag{4}$$

The case $W_{total} = 0$ is called an *isolated* pixel and no distribution occurs in this case. Otherwise, pixels receive intensity adjustments equal to their share of the error:

$$I_{st} \leftarrow I_{st} + error \times \hat{w}_{st}. \tag{5}$$

Note that the intensity adjustment of equation 5 might result in overflow or underflow. In such cases, the pixel is clamped to 0 or 255 and the excess is added to the residual. The residual error also accounts for isolated pixels, which can distribute none of their error to the neighborhood. We carry residual error forward to the next pixel in the process.

The above algorithm is fairly effective at preserving tone and structure, as our results will show. However, the raster scanning order is too inflexible; it introduces visible artifacts, and also ignores some weak edges. Despite our contrast enhancement scheme, weak edges might be missed; it might be that enough error is distributed to edge pixels to overcome their initial disposition. Figure 6 displays some missing weak edges in the “snail” example and Figure 3(a) shows the visual artifacts. To maintain fine details without losing much tone quality, we devised the following variant.

3.2. Dynamic Priority

Some results are shown in Figures 4 and 6 and indicate that good structure fidelity is achieved even by the basic method. However, the powerful virtue of the contrast-aware idea is impaired by the inflexible scanning order. Our idea is to process the pixels closer to black or to white first, and treat the intermediate pixels last, after they have received the error from the nearby more extreme-valued neighbors.

Only a small modification to the basic procedure is needed to implement this idea. We maintain a priority heap, sorting all pixels by their intensity distance to black or to white. Initially, the heap contains all pixels with their initial distances. At each step, the heap pops out a pixel with highest priority: of all remaining pixels, the one with the smallest distance to black or white. We apply the previous algorithm to this one pixel, assigning it a final value and distributing the error to its neighborhood. After the error distribution, many nearby pixels will have changed their intensities, and correspondingly their priorities. We push the new values onto the heap; in our implementation, there will be stale values in the heap, which we can discover and discard by checking the popped up pixel to verify that its priority is up-to-date. The process continues until the heap is empty, at which point all pixels will have been assigned a final value. In the dynamic priority variant, we found our best tradeoff between quality and speed using $k = 2$ and a mask size of 7 by 7.

Image	lion	mole	pelican	portrait	ribbon	road	arm	bat	cat	knee	snail	tree
Our variant method	31.96	34.29	42.19	39.29	38.70	35.33	42.18	36.85	32.86	39.17	40.58	39.14
Our basic method	34.02	36.81	43.16	40.91	39.28	37.14	41.22	39.28	36.07	38.47	41.25	41.77
Structure-aware halftoning	41.12	40.94	42.59	38.92	35.51	38.48	41.20	39.30	33.63	37.64	40.09	39.41
Ostromoukhov method	43.87	44.83	48.00	43.61	45.96	44.01	35.95	39.78	34.71	34.92	37.07	40.85
FS error diffusion	41.57	44.65	48.05	44.33	46.49	42.82	47.67	44.68	44.24	44.87	45.67	48.44

Table 1: Tone similarity measurement based on PSNR

From the results in Figures 1 and 6, this priority-based scheme provides better structure detail than does the basic method. In halftoning a uniform region, the pixels within the mask will have their priorities reduced by the distributed error; hence, the algorithm will choose a pixel outside of the current mask as the next pixel, rather than being forced to choose a neighboring pixel. Choosing a distant pixel reduces clumping, somewhat emulating Poisson disc behavior and producing a better spatial distribution. Also, within a mask, the error is distributed in such a way as to preserve contrast. An up-to-date local priority order lets us use all the available information in deciding which pixel to treat next, which includes the history of distributed errors. Empirically, doing so results in superior detail preservation.

4. Results and Evaluation

In the paper introducing SAED, Chang et al. [CAO09] stated that their results have higher tone similarity measurement and lower structure similarity measurement than the results from SAH [PQW*08]. We are mainly interested in structure similarity: therefore, most of our results are compared with results from SAH. We also provide the measurement data in Table 1, 2, and 3 for Ostromoukhov [Ost01] method and FSED [FS74] to benchmark against methods not specifically designed for structure preservation. Figures 4, 5, and 6 give a visual comparison of our methods with SAH and SAED.

All our evaluations are coded in Matlab. For comparison with SAH and SAED, we followed the respective authors' evaluation design, preprocessing both the original image and the result with an 11 by 11 Gaussian filter, using σ of 2.0 for tone measurement, 1.5 for structure measurement, and 0.5 for contrast measurement.

4.1. Tone Similarity

Tone similarity is usually measured by computing the PSNR (peak signal-to-noise ratio) between two images. From the comparisons given in Table 1, we see that our basic contrast-aware method usually attains higher tone similarity than SAH. Our variant contrast-aware approach has similar scores as SAH. One reason for a little lower tone matching for some examples is that revealing subtle details usually requires more black pixels than strict tone matching would allow. Another reason is that the basic method always diffuses the error directly into the nearby pixels while the variant method might transmit the error to a distant pixel – e.g., when the isolated situation happens. Figure 2 shows the comparison for the ramp intensity with recent methods.

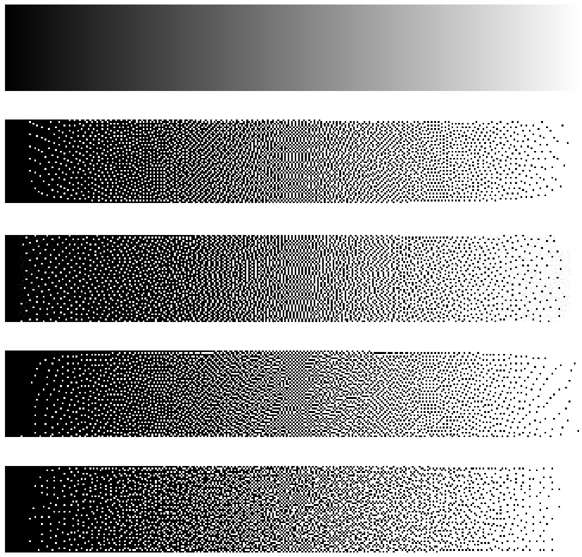


Figure 2: Comparison for ramp intensity (From top to bottom: the original image, error diffusion, SAH [PQW*08], our basic method and our variant method)

Notice that our dynamic priority method eliminates the undesirable patterns near intensity 128 in the ramp, visible in all previous methods.

4.2. Structure Similarity

We employ the mean structural similarity measure (MSSIM) [WBSS04] to measure structure similarity. Table 2 shows that both our methods achieve higher measurement in this test. A visual comparison can be found in Figure 5. Our result shows the leaves very clearly; the deepness of the shadows is stronger, and the faint halo along the right-hand edge of the main bush is shown well. It is even possible to see some texture in the far-away bush, which is not as visible in the result from SAH. The underlying reason for these differences is that our local contrast enhancement strategy makes sure to organize black pixels based on the structure edges, and even improves the edges by emphasizing the pixels that have values different from their neighbors.

Presumably the structure-aware halftoning method of Pang et al. would be able to produce better structure similarity given more time. However, using the optimization scheme as described, diminishing returns quickly set in and it might take a prohibitively long time to realize significant gains in structure quality. We have achieved better quality

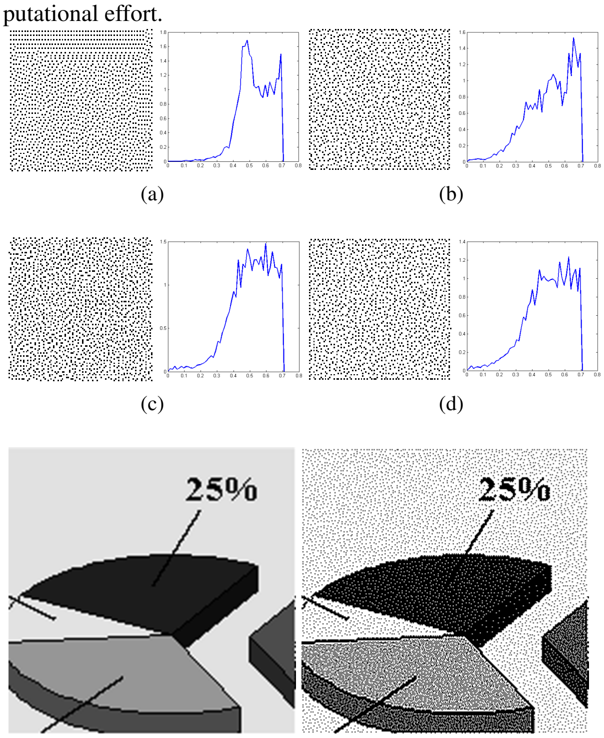
Image	lion	mole	pelican	portrait	ribbon	road	arm	bat	cat	knee	snail	tree
Our variant method	0.1074	0.1299	0.7853	0.3246	0.3576	0.3341	0.5738	0.2985	0.1514	0.4866	0.4682	0.1916
Our basic method	0.0898	0.1063	0.7691	0.2877	0.3292	0.3003	0.5511	0.2556	0.1142	0.4563	0.4386	0.1551
Structure-aware halftoning	0.0822	0.1011	0.7716	0.2745	0.2851	0.2906	0.5479	0.2678	0.1230	0.4534	0.4475	0.1539
Ostromoukhov method	0.0553	0.0616	0.7283	0.1861	0.2836	0.1879	0.3845	0.1617	0.0673	0.2951	0.3803	0.0317
FS error diffusion	0.0613	0.0680	0.7435	0.2043	0.2921	0.2070	0.5002	0.1620	0.0648	0.4359	0.4090	0.095

Table 2: Structure similarity measurement based on MSSIM codes proposed by Wang [WBSS04]

Image	lion	mole	pelican	portrait	ribbon	road	arm	bat	cat	knee	snail	tree
Our variant method	13.23	11.72	18.03	12.73	13.26	12.24	14.51	12.06	11.62	13.88	13.75	11.72
Our basic method	13.32	11.94	17.84	12.68	13.31	12.25	14.57	11.99	11.70	13.85	13.89	11.90
Structure-aware halftoning	12.56	11.12	17.54	12.11	12.26	11.62	13.97	11.95	11.16	13.55	13.46	11.13
Ostromoukhov method	12.23	10.64	16.17	11.24	12.04	10.55	12.22	11.62	10.40	11.40	12.15	10.02
FS error diffusion	12.49	10.95	16.69	11.71	12.37	11.10	13.58	11.04	10.63	12.48	12.67	10.74

Table 3: Contrast similarity measurement based on contrast PSNR

than was reported while using orders of magnitude less computational effort.



(a) (b)

(c) (d)

(e) A cartoon image (f) Improved variant method

Figure 3: Analysis for blue noise property. We show halftoned images and the RAPSD plots for four halftoning methods: (a) our basic method; (b) our variant method; (c) SAH; (d) our variant method with random tie-breaking of equal priorities. Next, application to real image: (e) input cartoon image; (f) halftoning of (e) with random tie-breaking.

4.3. Contrast Similarity

Because the HVS is more sensitive to contrast than absolute luminance, we introduce the contrast similarity to further validate our method. Contrast similarity is measured by calculating the local contrast from both the original image and the result and then finding the Mean Square Error (MSE) between the two contrast images. The contrast PSNR (CPSNR) is calculated in same the way as the tone similarity. We use the method proposed by Matkovic et al. [MNN*05] to measure contrast since it takes into account human perception. The perceptual luminance L is obtained from modifying the linear luminance with applying a gamma correction ($\gamma = 2.2$) and the local contrast is averaging the local difference among the neighbors. The equations are as follows,

$$L_{i,j} = 100 \times \sqrt{(g_{i,j})^{\gamma}} \tag{6}$$

$$lc_{i,j} = \frac{\sum_{(s,t) \in Neightbours} |L_{s,t} - L_{i,j}|}{4} \tag{7}$$

where $g_{i,j}$ is the grayscale levels, $\in [0,1]$, and (i,j) is the positon of the center pixel while (s,t) are represented for positions of four connected neighbors. As can be seen in Table 3, both our algorithms have superior performance to other methods on this metric.

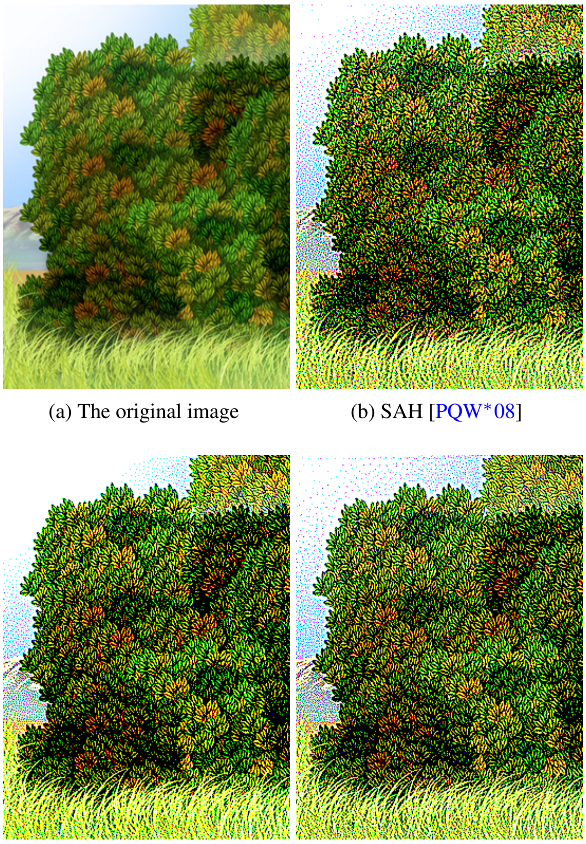
4.4. Blue Noise Property

The use of blue-noise property in terms of the radially averaged power spectrum density (RAPSD) is a widely used measure for the quality of halftoning methods.

Figure 3 gives a visual analysis of the blue-noise properties of our distribution. Figure 3(a) is generated by our basic method and its RAPSD is shown as well; it contains undesirable patterns. Using our variant method, we created Figure 3(b); it is of better quality but lacks the blue-noise property. The difficulty arises because the constant grayness image has the same priority for all pixels; ties are broken using scanning order, with concomitant artifacts. Figure 3(d) shows the result of a random tie-breaking mechanism: its RAPSD plot shows the high frequency region goes flatter than that from our basic method and thus the blue-noise property is improved a lot. The improved result has similar quality to the result from SAH, shown in Figure 3(c). Thus, if we expect to see uniform regions, such as in cartoon-style images like those of Figure 3(e) and (f), we should have the ability to choose arbitrarily among pixels of equal priority.

4.5. Analysis

Timing: Table 4 gives our timing values. To attain the best tradeoff between quality and speed, it takes 0.492 seconds for CPU to run our basic method and 2.955 seconds for our variant method to process halftoning on a 512×512 image with a 7×7 mask. SAH's paper [PQW*08] reported processing time of 2 minutes for a 512 by 512 image. It takes 6.74 seconds for SAED [CAO09] in CPU time to reach their best tradeoff while finishing the halftoning with a 16×16 mask. Thanks to our simple procedure, our methods achieve faster speed while preserving quality. Our timing measurements are based on an Intel Core Duo CPU E8400@ 3.0GHz with 3GB RAM.



(a) The original image (b) SAH [PQW*08]

(c) Our basic method (d) Our variant method

Figure 4: Color halftoning comparison.

The parameters: Mask size has a strong influence on quality. Usually, a larger mask size gives higher quality in structure preservation while a smaller mask produces higher tone matching. We believe that this also indicates a structure-tone tradeoff that will be encountered by other halftoning algorithms. The parameter k we employ in our weight function gives some control over the degree of tone matching and structure matching. For example, if k increases in some range around 0.5 to 4, the values for MSSIM and CPSNR are reduced, but the degree of tone matching is increased.

Mask size	5×5	7×7	9×9	11×11	13×13
Time (basic,secs)	0.27	0.492	0.775	1.225	1.706
Time(variant,secs)	2.202	2.955	3.12	3.608	4.047

Table 4: Time for different images and different mask sizes

Color halftoning: Digital color halftoning is a more complicated problem. For simplicity, both our basic and variant methods are applied separately to each RGB channel to accomplish color halftoning. Figure 4 shows a comparison with SAH [PQW*08]. Our results show the structure more clearly. Actually, color contrast is not a simple extension of luminance contrast. A more sophisticated color halftoning method would take into account interactions among colors.

5. Conclusion

In this paper we introduce contrast-aware methods as a powerful and useful extension to classic error diffusion. Due to taking advantage of local contrast enhancement, we achieve very high structure similarity with high tone quality. Our weight function maintains local contrast by attracting more error (or intensity) to light areas and increasing the likelihood that darker pixels will become black. The dynamic priority-aware scheme, based on the steeply droping property from the center to the far away distance in each mask emulates the Poisson-Disc behavior, thus generating a good spatial distribution. The idea of introducing priority scheme into halftoning is new and we demonstrate that it plays an important role in producing good results. From comparisons with recent halftoning methods, we conclude that our method is simple, easy to implement, totally automatic, effective, and has very fast speed. We also conclude that the contrast is a very important factor when we generate halftoning or other digital styles. Also we demonstrate it can be extended into color halftoning.

Limitations and Future work: Since the proposed methods are not optimal, the black pixels are not perfectly spatially distributed. In particular, sometimes clumping happens. Even though we showed good results for our method, we would like to further investigate its motivating assumption. Does higher contrast always have more appealing structure?

The influence of the shape of the mask should be researched further and interesting work might emerge. Other image features such as local histogram, texture features, entropy, statistical factors might be very useful to adjust the local contrast too. We mentioned before that color halftoning might be a future direction, and artistic styles generated through pixel management provide further research topics.

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(a) The original image

(b) Structure-aware halftoning [PQW*08]

(c) Structure-aware error diffusion [CAO09]

(d) Our variant method

Figure 5: Illustration "tree".

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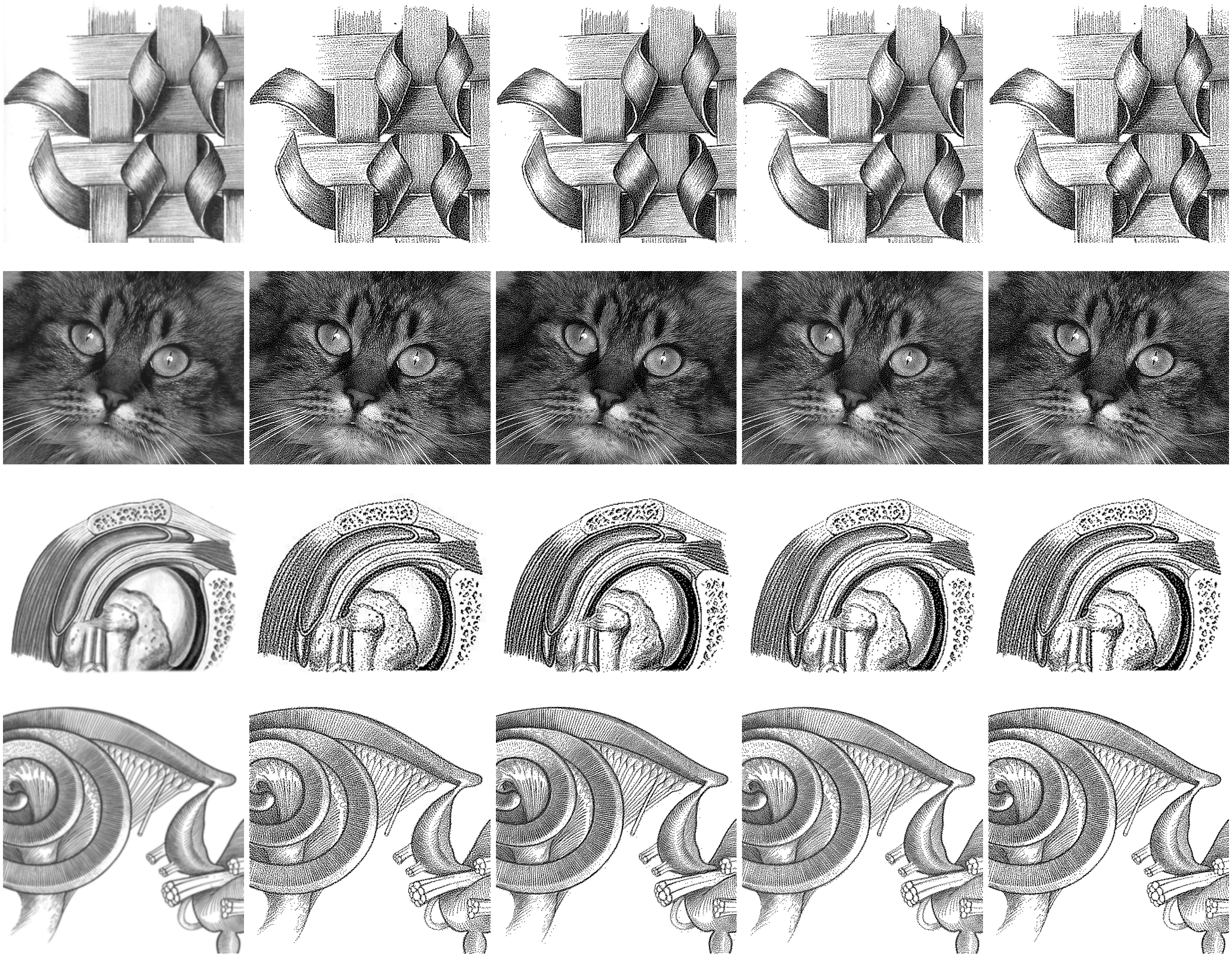
Figure 6: Illustrations and natural picture, “ribbon”, “cat”, “knee” and “snail”.

(a) The original image (b) SAH [PQW*08] (c) SAED [CAO09] (d) Our basic method (e) Our variant method



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