Edge Enhancement Issues In Half-Toning

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Abstract

The correct display of edges in half-toned images is necessary for accurate image reproduction. This problem has been addressed by pre-processing the image to enhance the edges or by altering the half-toning algorithm to account for edges. In this paper we present a post-processing edge enhancement technique that is applicable to all half-toning algorithms.

We identify two types of edge pixels in the image; dark and light edge pixels. Edges in an image are highlighted by setting the dark/light edge pixels to black/white. Our method was tested on a modern laser printer and hence our evaluation of the technique is restricted to clustered half-toning methods.

We evaluated the effect of enhancing edges by conducting a user *survey* to determine the perceived value of the different edge enhancement methods. The results of the user survey, while not statistically significant, indicate that our post-processing technique achieves comparable results to previous edge enhancement methods. Our technique is simple to implement and can be applied to any half-toning technique and thus is a good default edge-enhancing approach.

Keywords: Half-toning, edge enhancement.

Introduction

Our perception of an image is significantly dependent on the portrayal of edges in the image[Snyd85]. Thus one of the goals of half-toing has been the enhancement of edges in half-toned images. Two approaches have been tried, pre-processing edge-enhancement and adaptation of the half-toning algorithm to highlight the edges. As we show below these approaches do not always guarantee that a strong edge is drawn. We have chosen the highlighting of edges as our primary goal and would like to accomplish this independent of the half-toning method. In order to satisfy these two requirements we have developed a simple post-processing method that can guarantee that an edge is highlighted.

Evaluating the quality of half-toned images is a difficult task. Instead of simply presenting our technique we present the results of a user survey in which we asked the participants to compare the results of our technique with the results of previous edge-enhancement techniques. Rather than trying to evaluate the performance of our technique for all output devices we compared our technique with previous techniques using a modern laser printer†. The images were printed at the maximum printer resolution so that only one binary pixel is used per input gray-scale pixel.

Printing on laser printers is known to be problematic since individual pixels cannot be set in isolation. In order to compensate for this, clustered half-toning techniques are used. There are two types of clustered half-toning techniques; threshold matrix based and error diffusion. Clustered dither matrices [Ulic87] ensure that the black pixels are set in a dot like fashion usually growing from the center of the threshold matrix outwards. Error diffusion [Floy76, Knut87, Zhan93] fails when the display device cannot set a pixel independently. This is the case for modern laser printers where an isolated black pixel can be set but an isolated white pixel will tend to disappear. Clustered error-diffusion [Velh91, Velh95, Buch95] approximates the image region by region distributing error to the neighboring regions.

Both of these clustered half-toning approaches have the potential of placing clusters across an edge in the image. The placement of these clusters across edges in the image destroys the edges.

Ulichney [Ulic87] showed that it was desirable to have a blue noise power spectrum for areas of uniform intensity. Ulichney's work on blue noise error diffusion has

† The images were printed on a HP *LaserJet 5Si MX* at 600 dpi

motivated the development of blue noise masks [Mits91]. These are essentially large dither matrices with a blue noise power distribution. The reproduction of high frequency elements of the images is improved but there is no guarantee that important edges will be highlighted.

In this paper we present an overview of the literature on highlighting edges in clustered half-toned images. We discuss the strengths and weaknesses of the different approaches. We then introduce our post-processing method that can ensure that an edge is highlighted. This method is easy to implement. In order to evaluate our method we conducted a user survey. The results of this survey indicate that our technique performs as well as other edge enhancement methods when edge enhancement is appropriate.

Nomenclature and sample images

Intensity Values

We define the intensity of an image pixel as the amount of ink required in that pixel, 1 = black, 0 = white.

Edge pixels

We identify two types of edge pixels, light and dark. In order to determine whether a pixel is an edge pixel we evaluate an interest operator:

$$\delta_e = max(|I_{(x,y)} - I_{(i,j)}|)$$

where (i, j) are the 8 connected neighboring pixels of $I_{(x,y)}$. The sign of this value then tells us whether the pixel is a dark ($\delta_e > 0$) or a light ($\delta_e < 0$) edge pixel.

Example images

We have selected 2 images to illustrate the effects of our technique. These are a digitized pencil drawing, chosen because of the high number of edges it contains [Vogt73] (figure 4), and a painting with a mixture of smooth regions and some edges [Smit82] (figure 5).

Pre-processing Edge-Enhancement Techniques

Jarvis *et al.* [Jarv76] suggested the use of a preprocessing filter for enhancing the edges of the image. The image is convolved with the filter

$$I_{(x,y)} = \frac{I_{(x,y)} - \alpha\left[\sum_{i,j} I_{(i,j)}\right]}{1-\alpha}$$

where $I_{(i,j)}$ are the 8 neighbors of the pixel $I_{(x,y)}$ and α controls the amount of edge enhancement. Knuth [Knut87] also used this edge enhancement method with $\alpha = 0.9$. Zhang and Webber [Zhan93] reported the use of this pre-processing step with mixed results.

This edge enhancement step increases the contrast of the edge pixels within an image. When a large value is chosen for α the light edge pixels are made white and the dark edge pixels are made black. The important question is then whether or not the half-toning technique will preserve these enhanced edge pixels.

Consider the case where the edge pixels have been set to black or white. If the half-toning technique always sets white pixels to white and black pixels to black then these enhanced edge pixels will remain and the edge will be preserved. This is illustrated in figures 1–3.

Figure 1 contains a simple image with four vertical edges in it. The left most and right most edges have a strength of 0.15. The center two edges have a strength of 0.25. The image was enhanced using Jarvis's filter with $\alpha = 0.9$.

Ordered dither (clustered and dispersed) half-toning methods have the property that white pixels are set to white and black pixels are set to black. In figure 2 we see this situation in the center two edges. Both the light edge pixels and the dark edge pixels have been set to white and dark respectively. Contrast this with the edge produced on the two weaker edges (left and right) where the resulting edges are not highlighted as strongly since either the light or the dark edge pixel has not been set.

In figure 3 we see that edge enhancement does not result in highlighted edges when error-diffusion‡ [Velh91] is used because the error-diffusion technique may propagate error across edges thus reducing the contrast across the edge.

Adaptive Half-toning Techniques

Velho and Gomez [Velh91] showed that clustered dithering can easily be accomplished using error-diffusion. Using a space-filling curve as suggested by Witten and Neal [Witt82] they processed the image using segments of the curve. Each segment of the curve defines a region of the image whose average intensity is approximated by two clusters of black and white pixels. These clusters could straddle an edge and thus destroy it. Buchanan and Verevka§ [Buch95] and Velho and Gomez [Velh95] proposed adaptive clustered error diffusion methods that guaranteed that none of the approximating regions crossed a significant edge. However, there is no guarantee that black clusters from regions on either side of the edge may not be placed next to each other. When two black clusters are placed in this manner the result is that the edge is destroyed.

A second problem with this approach ([Buch95]) is that the approximating regions are made smaller. As the approximating regions are made smaller the size of

‡ Edges are destroyed in this error-difusion technique due to the clustering of pixels. If the pixels are not clustered as in [?] then the edges are not destroyed.

§ The third author's name was changed by the Ukrainian government from Verevka to Veryovka

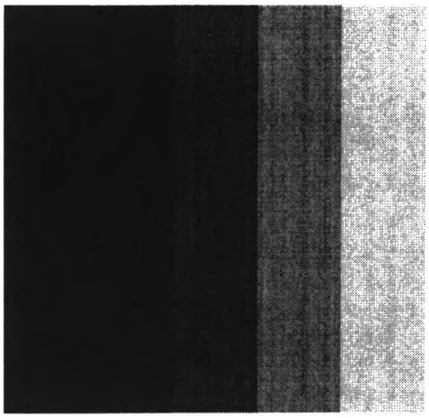

Figure 1: *Vertical bands used to illustrate edge enhancement artifacts. The intensity of the bands from left to right is 0.9, 0.75, 0.5, 0.25, 0.1. This means that the strength of the edges from left to right is 0.15, 0.25, 0.25, 0.15*

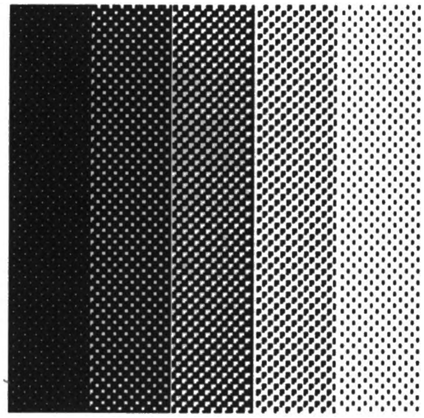

Figure 2: *Image half-toned using clustered ordered dither with 19 levels of gray. The image is pre-processed using Jarvis's filter with* $\alpha = 0.9$. *The left most-edge and the right-most edge are not strong enough to be completely highlighted using this method.*

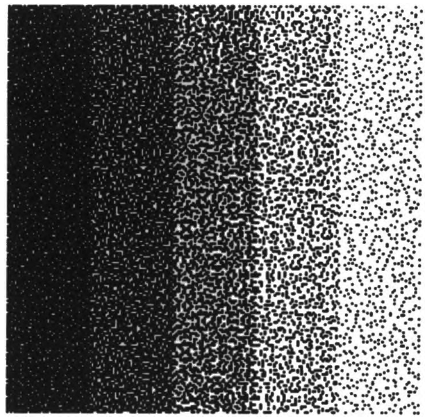

Figure 3: *Image half-toned using space-filling curve error-diffusion with a step size of 7. The image is pre-processed using Jarvis's filter with* $\alpha = 0.9$. *The enhanced edges are destroyed by the approximating clusters.*

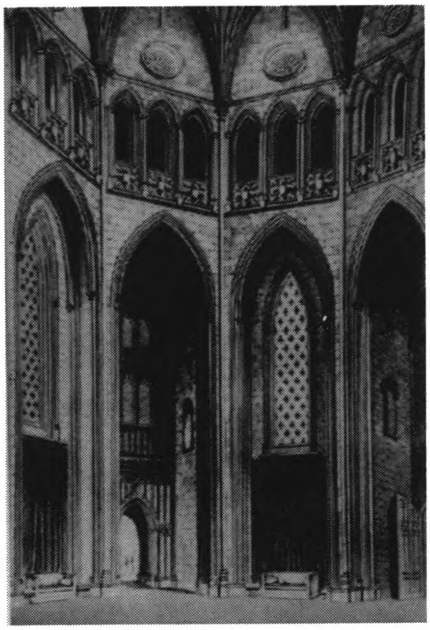

Figure 4: *Font Hill Abbey near Salisbury, Plate 4 in [Vogt73]. This pencil drawing was selected because of the high number of edge details present in the image. In particular, we draw the reader's attention to the rosettes in the upper arches.*

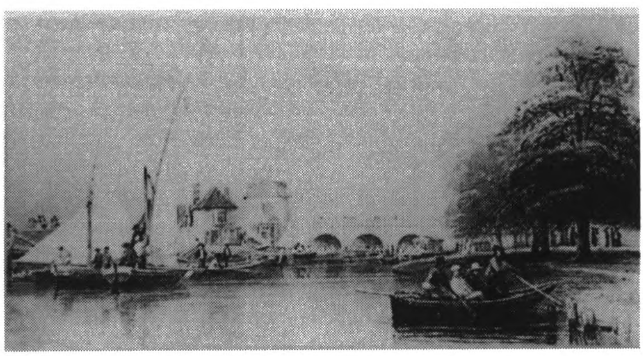

Figure 5: *Folly Bridge, Oxford, Plate 82 in [Smit82], this image was selected because of the large areas of uniform gray contrasted with subtle details. The darkness of this image combined with subtle edges make this a hard image to half-tone. This image was used for the user survey presented at the end of this paper.*

the clusters must also become smaller resulting in an increase in isolated pixels. As we discussed earlier this can result in poor image reproduction on laser printers. We can see this effect in figure 9 where we used an implementation of Buchanan and Verevka's method to print the image. The edge strength used to adjust the approximating region was $\frac{20}{255}$. The intended approximating region was 17 but the average approximating region size was 2.97. This results in a very dark image due to ink spread.

Buchanan and Verevka [Buch95] also suggested sorting the pixels within a region based on the original intensities. This ensures that the darkest pixels in the region are set to black. This results in a highlighting of the edges but changes the cluster shape. We have chosen to use this method as the edge enhancement method for clustered error-diffusion in our user survey (Plates T.4, T.8).

Post-processing Edge-Enhancement Technique

As stated above our primary goal is to produce half-toned images in which the highlighting of the edges is guaranteed. With this goal in mind we used a G-buffer [Sait90] approach to post-process the half-toned image. After the image is half-toned we search the input image for pixels that have a stronger edge than that specified edge strength parameter δ_e. Light edge pixels are set to white and dark edge pixels are set to black.

The results of enhancing the edges in this manner can be seen in Plates T.1, T.5, T.20, and T.24. Here we see the results of applying full edge enhancement to our two test images. This approach definitely highlights the edge, however this may be viewed as an over- emphasis of contrast. In order to allow the user to display the edge using less contrast we introduced two additional parameters δ_b and δ_w. These two parameters allow the user to specify when to set both light and dark edge pixels and when to set only one of them. A dark edge pixel is set if its edge strength is above the edge selection threshold δ_e and if $1 - I_{x,y} \leq \delta_b$. Similarly a light edge pixel is set if $I_{x,y} \leq \delta_w$. Thus the user can specify that light edge pixels are only set in relatively light regions and dark edge pixels are only set in dark areas. In figure 6 we show the relationship of the three user thresholds δ_e, δ_b, and δ_w.

By changing the values of these thresholds we can change how edges are highlighted. The first (δ_e) defines which edges are candidates for highlighting. In figures 7 and 8 we can compare the results of altering this parameter. In figure 7 we have used an edge strength of $\frac{20}{255}$ where as in figure 8 we used an edge strength of $\frac{60}{255}$. We draw the reader's attention to the circles around the rosettes which are less clear in figure 8.

In particular, when $\delta_e + \delta_b + \delta_w = 1$ we only emphasize one of the light or dark edge pixels associated with an edge. This gives us a minimal edge-enhancement. By changing the ratio of δ_b to δ_w we can bias the edge enhancement towards the light or dark end of the spectrum. Examples of this variation are shown in plates T.9, T.10, T.11, T.13, T.14, and T.15. Plates T.9 and T.13 show a centered minimal edge-highlighting. Figures T.10 and T.14 are produced using the same edge strength ($\delta_e = \frac{30}{255}$) but white edge pixels are set more often than the dark edge pixels. Minimal edge-highlighting biased towards the dark edge pixels is shown in plates T.11 and T.15.

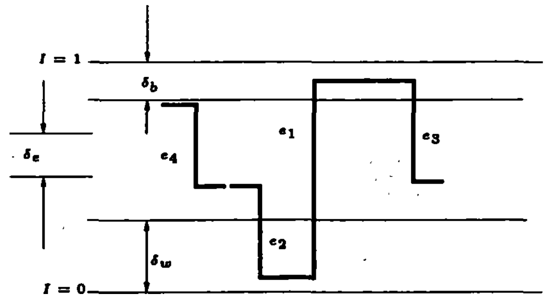

Figure 6: *The parameters used for edge enhancement are δ_e, δ_b, and δ_w. In this figure we illustrate an intensity profile that contains 4 edges (e_1, e_2, e_3, e_4) that have the property that their strength is larger than the cutoff threshold δ_e defined by the user. Each of these edges will be highlighted in a different manner: e_1 will be highlighted by setting both the dark and the light side of the pixel; e_2 will have the light side of the edge set to white; e_3 will have its dark edge pixel set to black; while e_4 will not be highlighted at all.*

User Survey

Image quality is largely a subjective matter. The technique we have discussed here allows us to highlight edges in half-toned images. In order to evaluate the effectiveness of our technique and its applicability to images we wanted to find the answers to the following three questions. In the appendix we have included the images used for the survey. These were printed at 600dpi on a HP *LaserJet 5 Si MX*.

1. In the context of clustered error-diffusion where pre-processing the image does not work: How does full edge enhancement compare with the edge enhancement technique presented by Buchanan and Verevka[Buch95]?

   The four images in this test were generated with full black and white edge enhancement, full white edge enhancement, full black edge enhancement, and by sorting prior to setting the pixels according to [Buch95]. Images used for this test are plates T.1-T.8.
2. Given a minimal edge enhancement is there any advantage to biasing the enhancement towards the light

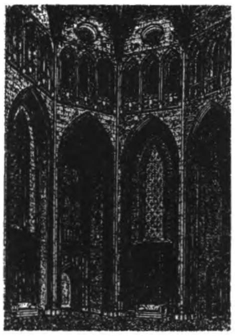

Figure 7: *Abbey picture printed using Space-Filling curve error-diffusion at 600 dpi. Edges whose strength is over $\frac{20}{255}$ are highlighted. Note the details around the rosettes.*

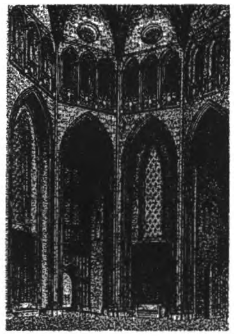

Figure 8: *Abbey picture printed using Space-Filling curve error-diffusion at 600 dpi. Edges whose strength is over $\frac{60}{255}$ are highlighted. Note the missing details around the rosettes.*

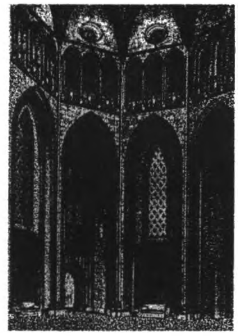

Figure 9: *Abbey picture printed using Adaptive Space-Filling curve error-diffusion [Buch85] at 600 dpi. The edge threshold used is $\frac{20}{255}$. Notice the complete lack of detail around the rosettes.*

edges or the dark edges?

It is clear that in some cases highlighting the light and dark edge pixels over emphasizes the edges. The images here compare a centered minimal edge enhancement with two edge enhancements biased towards the light and dark edges. A strongly enhanced image is included. This allows us to compare whether there is any preference between the strong edge enhancement and the minimal edge enhancement. Images used for this test are plates T.9-T.16.

3. How does this post-processing technique compare with pre-processing the edges with ordered dither?
Ordered dither half-toning preserves enhanced edges. We wished to investigate how this pre-processing technique compared with the post-processing technique that we presented in this paper. We have used two images generated using pre-processing ($\alpha = 0.5, 0.9$) and two images generated using post-processing, minimal edge enhancement, and maximal edge enhancement. Images used for this test are plates T.17-T.24.

Survey design

Our study involved 23 volunteers¶. Each user in our survey was presented with a booklet that contained the instructions for the survey on the first page. The second and third page contained high resolution full page renderings of the two test images 4 and 5. The remaining pages contained the test images, four to a page. The position of the images on the page was randomly selected.

¶ 8 female and 15 male
1 faculty, 1 staff member, 1 graduate student's spouse and 20 graduate students.

The six tests (T.1-T.4), (T.5-T.8), (T.9-T.12), (T.13-T.16), (T.17-T.20), (T.21-T.24) were also presented in random order. The users were asked to examine the high resolution versions of the images and were then asked to study each of the six tests without referencing the original images. On each of the test pages they were to indicate which they thought was the best image. The intent of this survey was to quickly get some feedback on the issues being addressed in this paper. The results of this survey are summarized in figure .

Conclusions from our user survey

Our user survey provided us with some information about the validity of enhancing edges. We feel confident making the following observations.

- The answer to questions 1 and 3 is that high-lighting the edges of an image in a post-processing step is equivalent to other methods in images with a significant number of edges.
  We make this claim based on the first and fifth test. In the first test Image_1 and Image_3 were preferred by 11 users versus 12 who preferred the image produced by sorting the pixels. In the fifth test where we compared the effect of pre-processing and post-processing with ordered dither 10 people chose one of the pre-processing methods and 13 chose one of the post-processing methods.
- The answer to question 2 is that there is no apparent benefit in biasing the edge highlighting towards the light or the dark edges.
  Biasing the edge enhancement towards black and white does not seem to generate a better image. We make this claim based on the first four tests in which the second and third options were by and large ignored by the users.

Question No.	Test	Test Image	No. of participants who chose image as best (Plate label)			
1	1	Abbey	8 (T.1)	0 (T.2)	3 (T.3)	12 (T.4)
	2	Bridge	1 (T.5)	1 (T.6)	0 (T.7)	21 (T.8)
2	3	Abbey	10 (T.9)	5 (T.10)	1 (T.11)	7 (T.12)
	4	Bridge	3 (T.13)	2 (T.14)	6 (T.15)	12 (T.16)
3	5	Abbey	9 (T.17)	1 (T.18)	4 (T.19)	9 (T.20)
	6	Bridge	15 (T.21)	0 (T.22)	2 (T.23)	6 (T.24)

Figure 10: *Summary of survey responses indicating how many people selected that image as the best image in the test. Each row corresponds to a different test. The labels in parenthesis indicate the plate used for the test.*

- There is no significant gain in post-processing edge-enhancing for images with few and subtle edges.
  We make this claim based on tests two and six. In test two the users by and large chose the image that did not have explicit edges highlighted. The comments seem to indicate that the introduction of edges into this image was undesirable. In test six the users chose the very subtle edge enhancement over the more aggressive edge enhancements.

Conclusions

We have presented a straight forward technique for enhancing edges in half-toned images. Our main contribution is a method that guarantees that the edges are highlighted. This post-processing approach can be used with any of the published half-toning methods. The enhancing of the edges is controlled by three user defined variables; strength of the edge, bias towards light edges, and bias towards dark edges. This technique works well in all half-toning applications. In particular we have shown that it is effective at highlighting edges in images being printed on laser printers at the maximum resolution of the printer where one binary pixel is being used to approximate the intensity of one of the original pixels.

The results of our user survey allowed us to perform a preliminary evaluation of our technique. We were not surprised to find that our technique produces similar results to other edge enhancement techniques in the context of clustered half-toning. This was seen both in the case of ordered dither and space-filling error diffusion half-toning. We were surprised to find that biased edge enhancement does not seem to result in better images.

We make no claims about the effectiveness of this technique in other contexts. In particular this post-processing technique needs to be evaluated on devices where single pixels can be set. The reason for this is that error-diffusion is quite good at preserving edges when the approximating region is a pixel. There is also a number of edge-enhancement approaches that must be evaluated in future experiments. The next step in this work is thus to perform this evaluation.

Thanks

We would like to thank the members of the Graphics lab who endured the preliminary versions of the survey, in particular we would like to thank Paul Ferry for his insightful critiques of this work. Steve Sutphen helped us with the photos of the sample images. The reviewers of this paper helped define the context of the paper.

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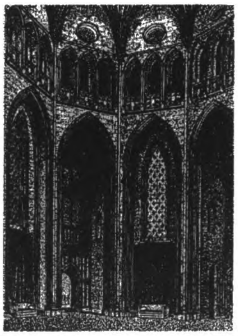
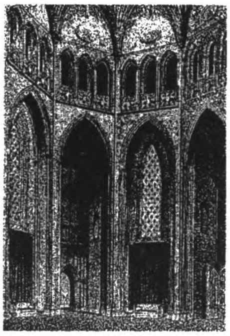
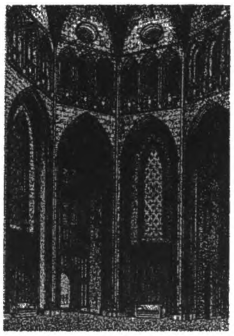


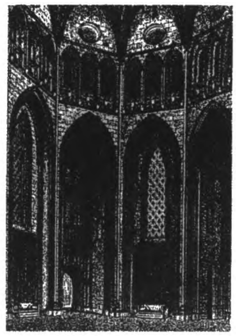
T.1: *Space-Filling curve*, $\delta_e = \frac{25}{255}, \delta_b = 1, \delta_w = 1$



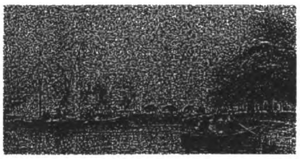
T.2: *Space-Filling curve*, $\delta_e = \frac{25}{255}, \delta_b = 0, \delta_w = 1$



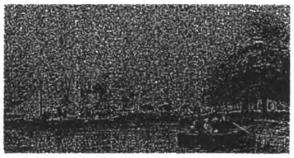
T.3: *Space-Filling curve*, $\delta_e = \frac{25}{255}, \delta_b = 1, \delta_w = 0$



T.4: *Sorted Space-Filling curve [Buch95].*

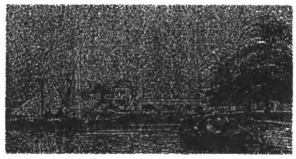


T.5: *Space-Filling curve*, $\delta_e = \frac{25}{255}, \delta_b = 1, \delta_w = 1$

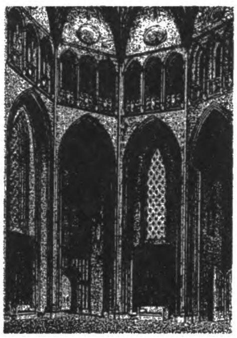


T.6: *Space-Filling curve*, $\delta_e = \frac{25}{255}, \delta_b = 0, \delta_w = 1$

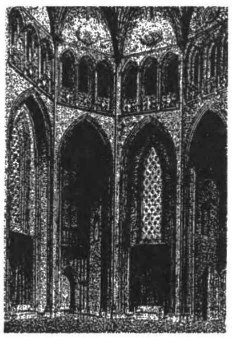
T.7: *Space-Filling curve*, $\delta_e = \frac{25}{255}, \delta_b = 1, \delta_w = 0$



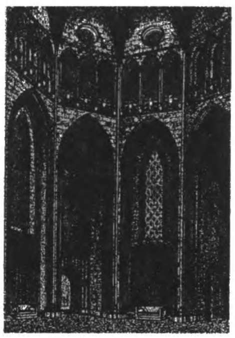
T.8: *Sorted Space-Filling curve [Buch95].*



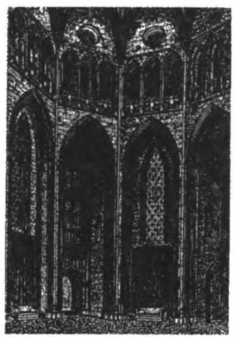
T.9: *Space-Filling curve*, $\delta_e = \frac{30}{255}, \delta_b = \frac{112}{255}, \delta_w = \frac{113}{255}$



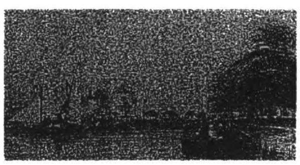
T.10: *Space-Filling curve*, $\delta_e = \frac{30}{255}, \delta_b = \frac{60}{255}, \delta_w = \frac{165}{255}$



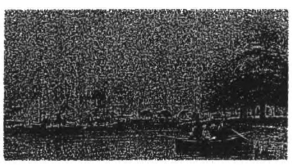
T.11: *Space-Filling curve*, $\delta_e = \frac{30}{255}, \delta_b = \frac{165}{255}, \delta_w = \frac{60}{255}$.



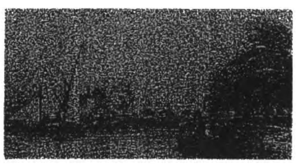
T.12: *Space-Filling curve*, $\delta_e = \frac{30}{255}, \delta_b = \frac{200}{255}, \delta_w = \frac{200}{255}$



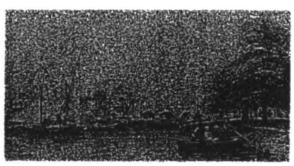
T.13: *Space-Filling curve*, $\delta_e = \frac{30}{255}, \delta_b = \frac{112}{255}, \delta_w = \frac{113}{255}$



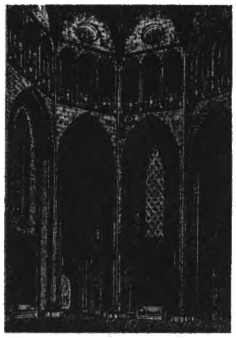
T.14: *Space-Filling curve*, $\delta_e = \frac{30}{255}, \delta_b = \frac{60}{255}, \delta_w = \frac{165}{255}$



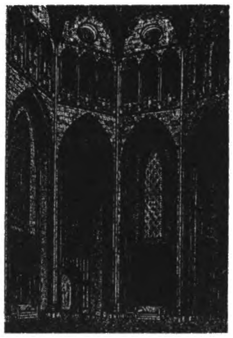
T.15: *Space-Filling curve*, $\delta_e = \frac{30}{255}, \delta_b = \frac{165}{255}, \delta_w = \frac{60}{255}$.



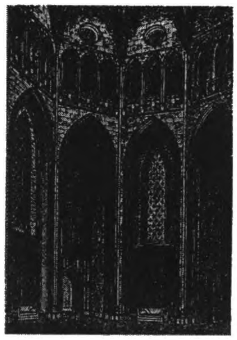
T.16: *Space-Filling curve*, $\delta_e = \frac{30}{255}, \delta_b = \frac{200}{255}, \delta_w = \frac{200}{255}$



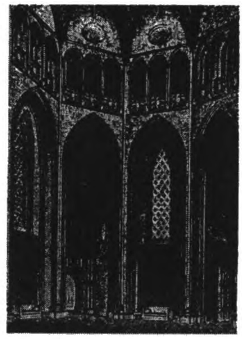
T.17: *Ordered dither, Jarvis pre-processing $\alpha = 0.5$*



T.18: *Ordered dither, Jarvis pre-processing $\alpha = .9$*



T.19: *Ordered dither, $\delta_e = \frac{30}{255}, \delta_b = \frac{112}{255}, \delta_w = \frac{113}{255}$*



T.20: *Ordered dither, $\delta_e = \frac{30}{255}, \delta_b = 1, \delta_w = 1.$*

T.21: *Ordered dither, Jarvis pre-processing $\alpha = 0.5$*

T.22: *Ordered dither, Jarvis pre-processing $\alpha = 0.9$*

T.23: *Ordered dither, $\delta_e = \frac{30}{255}, \delta_b = \frac{112}{255}, \delta_w = \frac{113}{255}.$*

T.24: *Ordered dither, $\delta_e = \frac{30}{255}, \delta_b = 1, \delta_w = 1.$*

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Appendix A: Images used in survey

1. How does post-processing compare with sorted clustered error diffusion?
   a. Full edge enhancement. Any edge with a strength greater than $\frac{25}{255}$ was highlighted. (T.1, T.5)
   b. Full black. The dark edge of any edge with a strength greater than $\frac{25}{255}$ was highlighted. (T.2, T.6)
   c. Full white. The light edge of any edge with a strength greater than $\frac{25}{255}$ was highlighted. (T.3, T.7)
   d. Buchanan and Verevka's method with the pixels sorted according to their intensity. The region size was 17. (T.4, T.8)
2. Is minimal edge enhancement worth it? What about biasing minimal edge enhancement?
   a. Minimal centered. $\delta_e = \frac{30}{255}$. $\delta_b = \frac{112}{255}, \delta_w = \frac{113}{255}$. (T.9, T.13)
   b. Minimal shifted to white.$\delta_e = \frac{30}{255}$. $\delta_b = \frac{60}{255}, \delta_w = \frac{165}{255}$. (T.10, T.14)
   c. Minimal shifted to black.$\delta_e = \frac{30}{255}$. $\delta_b = \frac{165}{255}, \delta_w = \frac{60}{255}$. (T.11, T.15)
   d. Double edge enhanced. $\delta_e = \frac{30}{255}$. $\delta_b = \frac{200}{255}, \delta_w = \frac{200}{255}$. (T.12, T.16)
3. For ordered dither how does post processing compare with pre-processing
   a. Medium pre-processing $\alpha = 0.5$ (T.17, T.21)
   b. Extreme pre-processing $\alpha = 0.9$ (T.18, T.22)
   c. Medium post-processing $\delta_e = \frac{30}{255}$. $\delta_b = \frac{112}{255}, \delta_w = \frac{113}{255}$. (T.19, T.23)
   d. Extreme post-processing $\delta_e = \frac{30}{255}$. $\delta_b = \frac{255}{255}, \delta_w = \frac{255}{255}$. Guaranteed that both edge pixels are set. (T.20, T.24)