

# Reaction-diffusion Woodcuts

D. P. Mesquita and M. Walter

*Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil*

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**Abstract:** Woodcuts are a traditional form of engraving, where paint is rolled over the surface of a carved wood block which will be used as a printing surface over a sheet of paper, so only the non-carved parts will be printed in the paper. In this paper, we present an approach for computer simulated woodcuts using reaction-diffusion as the underlying mechanism. First, we preprocess the segmented input image to generate a parameter map, containing values for each pixel of the image. This parameter map will be used as an input to control the reaction-diffusion processing, allowing different areas of the image to have distinct appearances, such as spots or stripes with varied size or direction, or areas with plain black or white color. Reaction-diffusion is then performed resulting in the raw appearance of the final image. After reaction-diffusion, we apply a thresholding filter to generate the final woodcut black and white appearance. Our results show that the final images look qualitatively similar to some styles of woodcuts, and add yet another possibility of computer generated artistic expression.

## 1 INTRODUCTION

Non-photorealistic rendering (NPR) (Strothotte and Schlechtweg, 2002), also known as *Expressive Rendering*, always looked for inspiration in the many forms of traditional artistic expression, trying to simulate the visual results of manual techniques. Since the early work of Haeberli (Haeberli, 1990) this area of research has seen major advances, being able to convincingly simulate natural media effects such as pencil drawing (Lu et al., 2012), oil painting in real-time and on mobile devices (Stuyck et al., 2017), watercolors (DiVerdi et al., 2013) (Wang et al., 2014), among many others. Hegde, Gatzidis, and Tian present a review of these artistic inspired results in (Hegde et al., 2013). Among the many relief printing and artistic techniques, such as etching or engraving, woodcuts have a distinct look due to their nature. A block of wood is used as the substrate where the artist draws the scene by carefully carving the wood with specialized tools. A thin layer of usually black paint is rolled over the wood substrate. The image is formed by evenly pressing a white paper over the wood block. The result is a black-and-white image where the woodgrain is visible and contributes to the appeal of the result.

In this paper, we present an approach to synthesize virtual woodcuts from natural images. We propose the use of reaction-diffusion (RD) systems as the

underlying mechanism to achieve the “feel and look” of woodcuts. Our main contribution is the introduction of RD addressing an artistic technique not yet explored, with visually pleasing results.

## 2 RELATED WORK

There has been countless approaches to render 2D input into artistic oriented renderings. The survey by Kyprianidis and colleagues (Kyprianidis et al., 2013) presents a taxonomy of Image-Based Artistic Renderings, as they name this class of techniques. Their focus was on the underlying methods and techniques being used rather than the artistic effect being simulated. The chapter by Lai and Rosin (Lai and Rosin, 2013) presents yet another survey with focus only on techniques working with reduced color palettes, typical of some artistic expressions such as comics, paper-cuts, and woodcuts.

Virtual woodcuts have not attracted much attention from graphics researchers. Perhaps because it is a less popular artistic technique than oil and watercolor paintings, for instance. Mizuno and colleagues (Mizuno et al., 2006) implemented a virtual analog of real woodcuts. With the use of a pressure sensitive pen and a tablet, their system allowed the user the feeling of carving real wood which could then be virtually printed. Their work is perhaps the first to bring

the attention to woodcuts in the NPR field. Their visual results, however, did not look very convincing, perhaps due to the need of artistic abilities to render a scene. A year later, Mello, Jung and Walter (Mello et al., 2007) introduced the first approach to synthesize woodcuts from natural images. Their approach applied a sequence of image processing operations to turn any image into a woodcut. Their results showed some similarity with real woodcuts. In 2011 Winnemoller presented an extension on the Difference-of-Gaussians operator allowing new results for artistic renderings from images (Winnemöller, 2011). Although his work did not particularly address woodcuts, he present one result mentioned as similar to woodcuts.

Just recently we have seen new approaches to virtual woodcuts. In 2015 a short paper (Li and Xu, 2015) addressed a particular style of color woodcuts, known as Yunnan woodcuts. These are color woodcuts that use only a single wood block that is recarved for each color. A year later the same researchers (Li and Xu, 2016) extended their previous work, paying particular attention to the color mixing intrinsic to the technique.

RD was introduced by Turing (Turing, 1952) as a mechanism to explain biological patterns. Basically, two chemicals react until they reach a stable state. Mapping their concentrations to colors we can see patterns of stripes, spots, and labyrinthine ones. Although it has been used in many graphics tasks before (Turk, 1991) (Kider Jr. et al., 2011) (Barros and Walter, 2017), just recently RD has been explored in NPR approaches. Chi and colleagues (Chi et al., 2016) explored these patterns for image stylization, achieving many visually interesting results. A year later, Jho and Lee (Jho and Lee, 2017) used the RD patterns in a new method of tonal depiction. Both did not address woodcuts.

In this paper, we introduce a new method for synthesizing virtual woodcuts from natural images adapting a RD system to the needs of rendering woodcut-like results. Our visual results compare favorably both with previous work and with commercial image manipulation software.

### 3 METHODOLOGY

Our method is subdivided into three steps: preprocessing, processing (RD) and post-processing (Fig. 1), as will be described below.

Briefly speaking, the preprocessing step receives as input an image and returns a parameter map, where each pixel receives a specific value for several param-

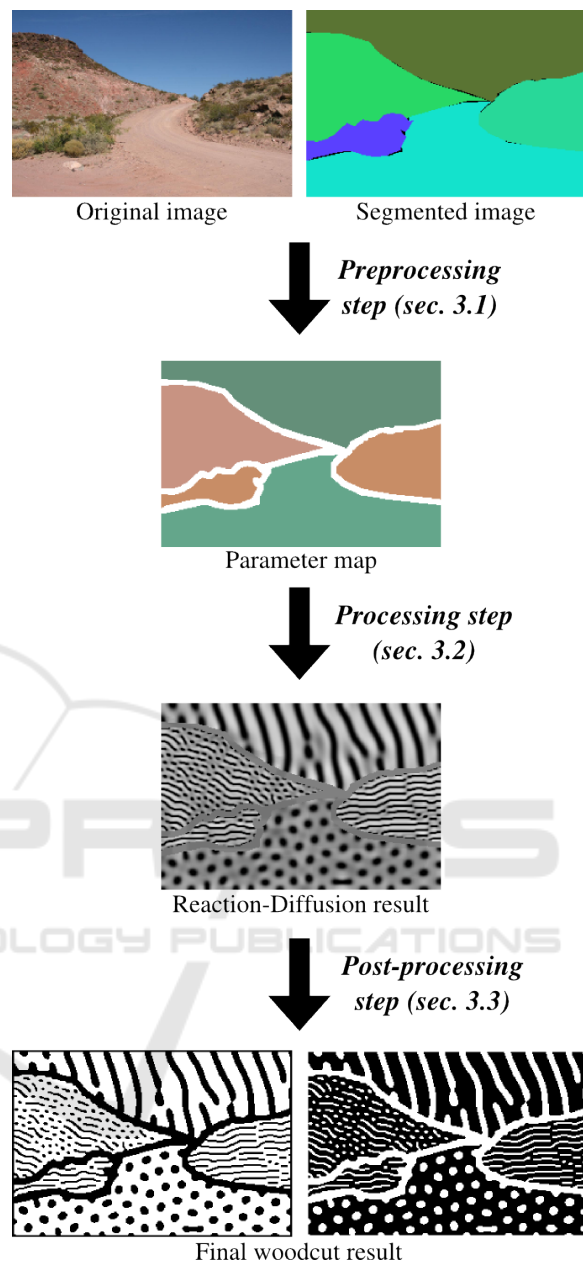


Figure 1: Pipeline of our methodology. First, we submit an image and its segmentation to the preprocessing step, in order to generate a parameter map. This parameter map is then used as basis for the RD process, generating then a raw woodcut-like image. Last, the RD result is filtered in a post-processing step in order to improve its appearance, generating the final woodcut image.

eters used in the processing step. The processing step runs the RD mechanism over the parameter map, setting the overall appearance of the final rendering. Finally, the post-processing step filters the RD result in order to enhance the similarity with a real woodcut image. We describe these steps below.

### 3.1 Preprocessing

Our algorithm receives as input both an image to be used as the basis for our final woodcut, and a segmentation of this image. The input image is converted to gray scale for all calculations used in our work. Instead of computing a segmentation, we used the dataset from ADE20k (Zhou et al., 2017). This dataset contains 22,210 images, from landscapes to indoor scenes, being visually adequate for our purposes. Besides, each image has a semantic segmentation. The segmented input image will be defined as a collection of regions. In Table 1 we present the parameters used in the preprocessing step, which will be explained throughout the text.

Table 1: User-defined parameters for the preprocessing step. Details about each parameter are given in the text.

| Parameter    | Default Value     |
|--------------|-------------------|
| $n_{dilate}$ | 1                 |
| $T_{low}$    | 25                |
| $T_{high}$   | 210               |
| $T_{size}$   | 500 pixels        |
| $k$          | {1, 5, 9, 13, 17} |
| $S_{min}$    | 0.005             |
| $S_{max}$    | 0.015             |
| $T_{diff}$   | 5.0               |
| $S_0$        | 0.010             |

The first step is to discriminate the parts of the image where no RD pattern will be generated, and instead a plain black or white color will be applied. First, from observation of real woodcuts, we define the borders of the segmented regions as black. These borders define the scene and so they should appear in the final woodcut as black strokes. The borders can be thickened to the desired size by a dilate operation, where, for every pixel in a binarized version of the image (where borders are black and other pixels are white), a kernel with dimensions  $5 \times 5$  is used: if any pixel inside this kernel is black, then the pixel in question is marked as black; otherwise it is white. This operation can be repeated  $n_{dilate}$  times. Larger kernels and/or larger values of  $n_{dilate}$  result in thicker borders, with smaller regions being absorbed into them.

According to (Mello et al., 2007), in real woodcuts the brightest regions are white, while the darkest ones are black, in both cases without any discernible stroke pattern. To reproduce this appearance, we use the same mechanism of their work, where two thresholds,  $T_{low}$  and  $T_{high}$ , are used; then we mark as white and black any regions whose average gray-scale color intensity is, respectively, higher than  $T_{high}$  and lower than  $T_{low}$ . Finally, to reduce unnecessary noise, we merge the smallest regions, whose area (i.e., the num-

ber of pixels) is smaller than a given threshold,  $T_{size}$ , into the borders, by marking these regions as black. Fig. 2c shows an example of the black and white generated from this part of the preprocessing step.

To allow a variation of detail levels for different parts of the image, we compute, for each pixel, a value for a RD parameter related to the size of structures generated by this mechanism called  $S$  (Bard and Lauder, 1974). We adapted the method from Hertzmann (Hertzmann, 1998) for this task. In that work, different detail levels in a painting are simulated by using distinct brush sizes in sequential steps, such that regions where fine detail is needed are painted with smaller brushes than other parts of the image, drawing more attention toward these regions. In our work, more detailed areas receive a higher value of  $S$ , resulting in smaller structures and thus increased preservation of details.

To implement this feature, we defined the following parameters: a list of integers  $k$ , the maximum  $S_{max}$  and minimum  $S_{min}$  values of  $S$ , and an error threshold  $T_{diff}$ . First, we mark all pixels as  $S_{max}$ . Then, for each integer  $k_i$ , starting from the smallest one, we generate a reference image by performing a Gaussian blur using a  $k_i \times k_i$  kernel (noting that larger values for  $k_i$  result in more blurred images, and so more different than the original). For every pixel, we compute the average pixel-to-pixel difference between the reference image and the original one for the entire neighborhood of this pixel, in a window with the same dimensions as the blur kernel. If this area difference is smaller than  $T_{diff}$ , we consider that the area around this pixel did not change too much between the blurred image and the original one, being consequently less detailed. We mark this pixel as the value of  $S$  corresponding to this kernel, calculated as:

$$S_i = S_{max} + m * (k_i - \min k)$$

$$m = \frac{S_{max} - S_{min}}{\min k - \max k}$$

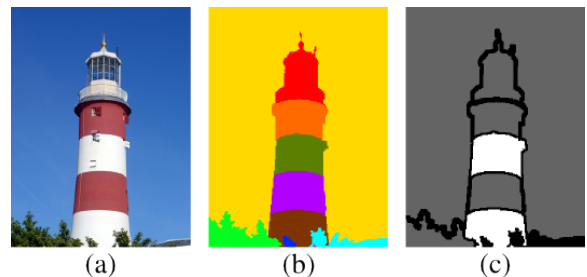


Figure 2: Lighthouse image used in our tests. (a) Original image from (Mello et al., 2007). (b) Manual segmentation of this image. (c) Borders and areas without RD, calculated in the preprocessing step, already painted as white and black. Areas where RD will occur are marked as gray.

After computing  $S$  for every pixel, we set a unique  $S$  for each region by computing the average  $S$  inside that region. By doing that, we ensure that inside a region all strokes will have the same size, improving structure size coherence for the result.

The parameter  $T_{diff}$  affects the average level of detail and size of strokes: smaller values for  $T_{diff}$  reduce the chance of every step to set a smaller value for  $S$  in the comparison between the original image and the blurred one, resulting on larger values for  $S$  and consequently smaller strokes, and a more detailed final result.

After that, we need to calculate the orientation of strokes. In our work, we have three options: a) orientation by region, b) orientation by pixel, and c) adaptive orientation. In the orientation by region, every pixel inside a given region will have the same orientation, so strokes will be parallel to each other inside the same region. As (Mello et al., 2007) observed, the wood carvings tend to initiate in the brighter parts of a region, so for every region we will start the strokes from the brighter point near region borders. Firstly, for each pixel of a given region which has at least one border pixel as neighbor, we test the average luminance for a  $5 \times 5$  window. We retrieve the pixel with the highest average luminance inside its corresponding window. Then, we compute the center pixel of every region as the average of the horizontal and vertical positions of every pixel in that region. To find the orientation angle of a region we compute the slope of the line formed by these two pixels: the border pixel with the largest average luminance in its surroundings and the central pixel, as follows:

$$\theta_{reg} = \arctan \frac{d_y - c_y}{d_x - c_x}$$

where  $\theta_{reg}$  is the orientation of strokes for a given region,  $d$  is the boundary pixel and  $c$  is the central pixel of a given region.

When calculating orientation by pixel, it is possible to set different pixel-specific values for  $\theta$ , which allows the contour of small details to appear in the resulting image. Our method for such calculation is based on local orientation of luminance as used by (Mello et al., 2007) and (Li and Xu, 2016). First, for each pixel  $(i, j)$  in the image, we compute the local average orientation of luminance  $\Theta$  in a  $5 \times 5$  window  $W$  centered in that pixel as follows:

$$\Theta_{i,j} = \frac{1}{2} \tan^{-1} \left( \frac{V_x(i,j)}{V_y(i,j)} \right)$$

where

$$V_x(i,j) = \sum_{(u,v) \in W} 2G_x(u,v)G_y(u,v)$$

$$V_y(i,j) = \sum_{(u,v) \in W} (G_x(u,v)^2 - G_y(u,v)^2)$$

and  $G_x$  and  $G_y$  are the image gradients in the  $x$  and  $y$  directions, calculated using the Sobel operator.

To orient the strokes preserving the contour details of the original image, their orientation should be perpendicular to the local average orientation of luminance  $\Theta$ . This happens because  $\Theta$  follows the direction of color gradients, i.e., it goes from black areas to white areas or vice-versa, being thus perpendicular to any existing line in the image (since the lines have more or less the same color). So, the stroke orientation  $\theta$  for a pixel is given by the following formula:

$$\theta_{i,j} = \frac{\pi}{2} + \Theta_{i,j}$$

While more complex objects as an human body or decorated buildings would need a finer level of detail, in background areas as the sky a single orientation works better, so the user would focus on the foreground instead of the background. The adaptive orientation method allows us to use both methods, orientation by region or by pixel, for different areas of the image, depending on the detail level required by that region. This detail level was encoded by the value of  $S$  calculated for that region previously. For a given region with a  $S$  value equals to  $S_{region}$ , if  $S_{region} > S_{\theta}$  (an user-defined threshold), then that region will use orientation by pixel; otherwise, the region will use orientation by region. Thus, regions with higher values for  $S$ , and consequently more details in the original image, will have these details preserved in the final woodcut, using a pixel-specific orientation. Less detailed regions will have a single orientation, enhancing their status as background regions.

Many real woodcuts show, besides lines and flat color areas, dots or other similar structures. In our RD system, it is possible to control which regions will have stripes or spots. We simulate this pattern diversity by setting different values of a parameter called  $\delta$  for every region. We considered brighter areas to have spots and darker ones to have stripes, using the average color of each region to compute this parameter. We will describe in the next section how this parameter works, when we will detail the main engine of our system, the RD process.

At the end of the preprocessing step, we save an image with the same dimensions of the original to be used as input for the RD process, where different color channels are used to set the local value of different parameters calculated in this step as follows: red for  $S$ , green for  $\delta$ , and blue for the orientation angle  $\theta_{reg}$ . Also, the value corresponding to plain white (255 for all channels) is interpreted as absence of RD for that pixel.

Alternatively, it is possible to use an image without segmentation, for cases where a segmentation is not available. In this case, there will be no borders or regions without RD,  $\theta$  will necessarily be defined by pixel and not by region, and each pixel will have a different value for  $S$ , since there will be no region to compute the average value for this parameter.

### 3.2 Processing

To generate the pattern of strokes, we use a RD system, specifically the non-linear system defined by (Turing, 1952) and later used by (Bard, 1981) (Bard and Lauder, 1974). In Table 2 we present the parameters defined in the processing step. This system is expressed by the set of partial differential equations below:

$$\begin{aligned}\frac{\partial a}{\partial t} &= S(16.0 - ab) + D_a \nabla^2 a \\ \frac{\partial b}{\partial t} &= S(ab - b - \beta) + D_b \nabla^2 b\end{aligned}$$

Here,  $a$  and  $b$  represent the concentration of morphogens (the substances responsible for generate patterns in Turing's theory),  $\partial a/\partial t$  and  $\partial b/\partial t$  the respective rates of variation in time,  $\nabla^2 a$  and  $\nabla^2 b$  the Laplacian representing the spatial variation of the morphogens (so they can diffuse from areas of higher concentration to areas of lower concentration).  $D_a$  and  $D_b$  the diffusion coefficients, and  $S$  a constant representing the speed of chemical reactions (and, as already mentioned, related to the size of structures generated by the RD process).  $\beta$  is added to generate the initial spatial heterogeneity in order to start the pattern formation process; they have a base value and can vary in a given interval following a uniform distribution. For our simulations,  $\beta = 12.0 \pm 0.05$ .

Table 2: User-defined parameters for the processing step. Details about each parameter are given in the text.

| Parameter      | Default Value |
|----------------|---------------|
| $D_{ah}$       | 0.125         |
| $D_{av}$       | 0.125         |
| $D_{bh}$       | 0.030         |
| $D_{bv}$       | 0.025         |
| $t$            | 16,000        |
| $\delta_{min}$ | 0.5           |
| $\delta_{max}$ | 1.5           |
| $M_{white}$    | 8.0           |
| $M_{black}$    | 0.0           |

To solve this system numerically, we discretized it spatially by a grid of pixels, and temporally with dis-

crete steps. The changes of  $a$  and  $b$  for a given pixel in a single step are given by the following equations:

$$\begin{aligned}\Delta a_{i,j} &= S(16.0 - a_{i,j}b_{i,j}) + D_a d_a \\ \Delta b_{i,j} &= S(a_{i,j}b_{i,j} - b_{i,j} - \beta_{i,j}) + D_b d_b \\ d_a &= a_{i-1,j} + a_{i+1,j} + a_{i,j-1} + a_{i,j+1} - 4a_{i,j} \\ d_b &= b_{i-1,j} + b_{i+1,j} + b_{i,j-1} + b_{i,j+1} - 4b_{i,j} \\ a &\geq 0, b \geq 0\end{aligned}$$

where  $i$  and  $j$  represent respectively the vertical and the horizontal position of the pixel in question. The total number of steps can be defined by the user as the parameter  $t$ . In the initialization, all pixels receive the same value  $a_0 = 4$  for  $a$  and  $b_0 = 4$  for  $b$ . The diffusion component for a morphogen can be written as a kernel; in this case, the matrix corresponding to this kernel is the following:

$$D = \begin{bmatrix} 0 & 1 & 0 \\ 1 & -4 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

As we described before, a parameter map, computed in the preprocessing step, is loaded into the RD system to allow different behaviors for each part of the image, particularly regarding the size of stripes and spots ( $S$ ), distinction between spots and stripes ( $\delta$ ), orientation of stripes ( $\theta$ ), and absence of RD (morphogens will not be generated neither travel from or to a given pixel).

The RD system described above is isotropic regarding the diffusion; in order to properly control the direction of stripes and thus orient the resulting pattern, we modified the diffusion term as in (Witkin and Kass, 1991), using the parameter map for  $\theta$ .

In that work, anisotropy is added by first setting two different diffusion coefficients for each axis in the bidimensional space, which allows the pattern to be elongated in the vertical or horizontal direction. Particularly, if the diffusion coefficient for the morphogen  $b$  is larger in an axis than in another, parallel horizontal stripes are formed, a pattern common in many wood carving images. These stripes are parallel to the axis where the diffusion coefficient is larger.

To allow this stretching in any direction, the diffusion directions are rotated by an angle. If we set the horizontal diffusion coefficient of  $b$ ,  $D_{bh}$ , to be higher than the vertical one,  $D_{bv}$ , then stripes will be parallel to the horizontal axis; rotating this system by an angle will also rotate the stripes by the same angle, so it is possible to control the orientation of stripes.

For the morphogen  $a$  in a given pixel with coordinates  $(i, j)$ , the rotated diffusion matrix to be used as the diffusion kernel is the following:

$$D_{ij} = \begin{bmatrix} -a_{12} & 2a_{22} & a_{12} \\ 2a_{11} & -4a_{11} - 4a_{22} & 2a_{11} \\ a_{12} & 2a_{22} & -a_{12} \end{bmatrix}$$

$$a_{11} = D_{ah} \cos^2 \theta_{ij} + D_{av} \sin^2 \theta_{ij}$$

$$a_{12} = (D_{av} - D_{ah}) \cos \theta_{ij} \sin \theta_{ij}$$

$$a_{22} = D_{av} \cos^2 \theta_{ij} + D_{ah} \sin^2 \theta_{ij}$$

$D_{ah}$  and  $D_{av}$  are the diffusion coefficients of  $a$  in the horizontal and vertical direction, respectively, and  $\theta_{ij}$  is the orientation angle for the pixel  $(i, j)$ , provided by the parameter map calculated in the preprocessing step. An analog matrix is used for the morphogen  $b$ . For more details regarding the mathematical formulation of this anisotropic RD system, consult (Witkin and Kass, 1991).

To form both spots and stripes in the same image, we use the parameter map of  $\delta$ . If the difference between the diffusion coefficients of  $b$  in a given direction is not so large, the stripes are broken after an interval; reducing even more this difference can result in spots slightly stretched in the direction of the larger diffusion coefficient. Consequently, by allowing different areas of the image to have a relatively larger or smaller value for this difference, it is possible to change the pattern obtained for each area. For each pixel, this information is encoded in the input image as the parameter  $\delta$ , which is interpreted by the system as a floating point number, varying between  $\delta_{min}$  and  $\delta_{max}$ , to be multiplied by  $D_{bv}$  (the vertical diffusion coefficient of  $b$ ) for that pixel. Since in our simulations we always have  $D_{bh} > D_{bv}$  (so the stripes are parallel to the orientation angle), values larger than 1 for  $\delta$  tend to form spots or broken stripes, while values smaller than 1 result in continuous, parallel lines. Increasing the difference between  $\delta_{min}$  and  $\delta_{max}$  allows more pattern differences among regions, while a small difference makes all regions to have the same kind of structure.

To save the result of the RD simulation into an image, we need to translate the morphogen concentrations into a color intensity. Our system allows two options for that: dynamic and static. In the dynamic option, the maximum concentration for the entire grid is treated as plain white (255 in RGB), while the minimum concentration is considered as plain black (0 in RGB); intermediate values are linearly interpolated from these extremes. The static option introduces two

limits,  $M_{white}$  and  $M_{black}$ , so any pixel with a morphogen concentration above  $M_{white}$  will be translated as white, while the ones with a concentration below  $M_{black}$  will be painted as black. This option is useful in certain simulations where some points have a very high morphogen concentration, leading most of the image to be saved as dark gray, reducing the contrast and disallowing the formation of a pattern during post-processing binarization (see sec. 3.3 below). It is also possible to choose which morphogen will be converted to the color intensities.

### 3.3 Post-processing

To enhance the similarity with real woodcuts, we post-process the resulting image from the processing step. First, we recover from the preprocessing step the information about plain black and plain white regions, where RD did not occur, painting these areas accordingly.

To reduce noise, we apply a median filter with a  $3 \times 3$  kernel over the image. After that, to get the aspect of an actual woodcut with white background and black strokes, the result from every median filter is submitted to thresholding using Otsu's technique (Otsu, 1979), resulting in a black and white binary image. To generate a white-line woodcut, with a dark background and white strokes, we simply invert the black and white pixels generated by the Otsu binarization (i.e. the negative of the image). According to Mello et al. (Mello et al., 2007), real woodcuts are not a binary, black and white image, but contain some tones of gray, particularly in the borders of strokes, due to imperfections occurred in the carving and the printing process. To simulate this, an optional filter to smooth the resulting image, as introduced in Mello's et al. work (Mello et al., 2007), can be applied to the result of Otsu binarization. The kernel used is the weight average kernel:

$$M = \begin{bmatrix} 1 & 2 & 1 \\ 2 & 10 & 2 \\ 1 & 2 & 1 \end{bmatrix}$$

## 4 EXPERIMENTAL RESULTS

In this section we present our synthesized woodcuts using the defined methodology. All images were made with the default values for the parameters, with  $\theta$  calculated by region, using the dynamic visualization option over the morphogen  $b$  and without the optional smoothing filter, unless stated otherwise.

Fig. 3 illustrates the flexibility of our system. For the same input image, many woodcut variations are possible by adjusting the parameters. Different regions can present distinct patterns, which eases the identification of image parts (Figs. 3d and 7). Figs. 3e and 3f show homogeneous patterns (stripes and spots, respectively) due to setting a unique value for  $\delta$  in the entire image. By setting a smaller difference between  $\delta_{min}$  and  $\delta_{max}$  the pattern difference is more nuanced, although still present, as some regions show longer stripes than others (Fig. 3g). Reducing the val-

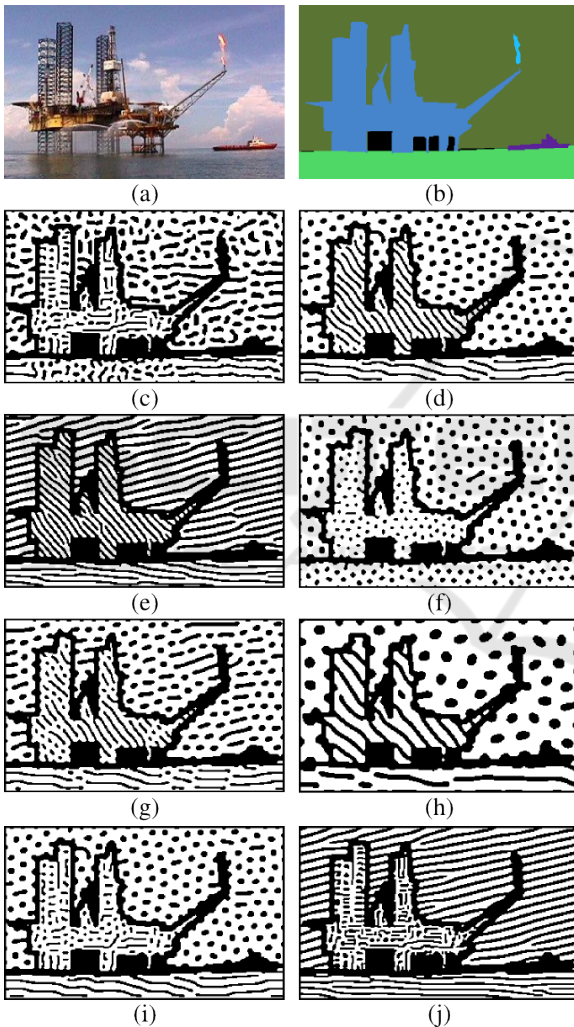


Figure 3: (a) Original image from the ADE20k dataset (Zhou et al., 2017). (b) Segmentation of the image from the ADE20k dataset. (c) Result for  $\theta$  calculated by pixel ( $D_{bh} = 0.040$ ,  $D_{bv} = 0.020$ , static visualization). (d) Result using the default value for parameters. (e) Result for  $\delta_{max} = 0.5$ . (f) Result for  $\delta_{min} = 1.2$  and  $\delta_{max} = 1.2$ . (g) Result for  $\delta_{min} = 0.8$  and  $\delta_{max} = 1.2$ . (h) Result for  $S_{min} = 0.002$  and  $S_{max} = 0.005$ . (i) Result for adaptive orientation (with static visualization). (j) Result for adaptive orientation ( $D_{bh} = 0.040$ ,  $D_{bv} = 0.020$ ,  $\delta_{max} = 0.5$  and static visualization).

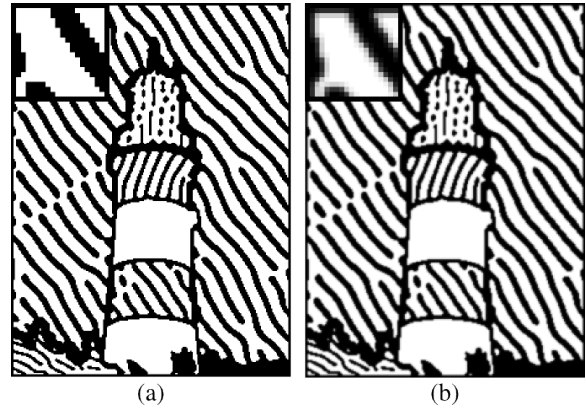


Figure 4: Example of the post-processing smoothing optional step (with  $k = \{1, 11, 21\}$  and  $T_{diff} = 10.0$ ). In the top left, a close-up of the result. (a) Result without smoothing. (b) Result with smoothing.

ues for  $S$  makes the stripes and spots bigger (Figs. 3h and 8). When allowing each pixel to have their own stroke orientation  $\theta$ , it is possible to preserve details of the original image from inside the regions (Figs. 3c, 9, 11 and 12). Adaptive orientation can only be used on specific parts of the image, allowing detail preservation for the most detailed regions while other regions have a more consistent single pattern (Figs. 3i, 3j, 6b and 10).

Fig. 6 shows the result for different border widths, calculated in the start of the preprocessing step. It should be noted that orientation angle for regions where  $\theta$  was calculated by region suffered some alterations among these results, due to the dilating process changing which was the brightest pixel from the region limit.

Fig. 4 compares the result with and without the optional smoothing filter. On one hand, smoothing filter reduces the aliasing, but the image seems a bit blurred. Some of our user-defined parameters did not yield interesting results, so we keep them fixed for all our simulations, such as  $T_{low}$ ,  $T_{high}$ ,  $D_{ah}$ ,  $D_{av}$ ,  $t$ ,  $M_{white}$  and  $M_{black}$ .

Validation is a difficult task in the general area of NPR (Isenberg, 2013). A quantitative evaluation is hard since there are no specific attributes that can be measured and compared. We perform a qualitative comparison against the previous results addressing woodcuts known in the literature, using a lighthouse image used in (Mello et al., 2007) and (Li and Xu, 2015) (Fig. 2a); to test this image, we did a manual segmentation over it (Fig. 2b). Comparing with Mello's work (Fig. 5a), our results (Fig. 5e and 5f) have a different appearance, with directional stripes resembling actual strokes, expanding the range of styles which can be generated. On the other hand,

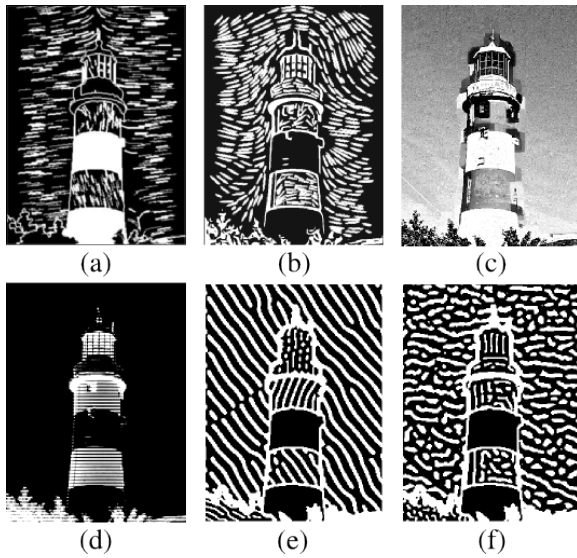


Figure 5: Comparison between different methods for generating woodcuts (for Fig. 2a). (a) Mello’s result (Mello et al., 2007). (b) Li’s result (Li and Xu, 2016). (c) Simplify 3 Preset List (Photoshop plugin) result for the Wood Carving option (Topaz Labs, 2018). (d) Result of a GIMP pipeline to generate a woodcut-like image (Welch, 2018). (e) Our result (with  $k = \{1, 11, 21\}$ ,  $T_{diff} = 10.0$  and inverted colors). (f) Our result for  $\theta$  calculated by pixel (with  $k = \{1, 11, 21\}$ ,  $T_{diff} = 10.0$ ,  $D_{bh} = 0.040$ ,  $D_{bv} = 0.020$ , static visualization, and inverted colors).

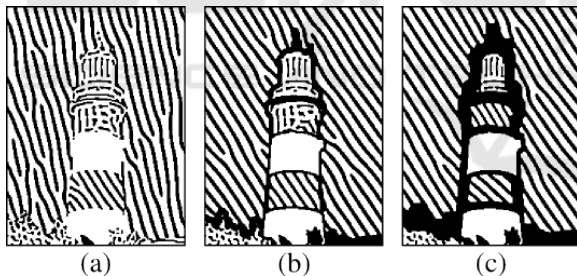


Figure 6: Comparison between different border widths, obtained by varying the value of  $n_{dilate}$  (for Fig. 2a with  $k = \{1, 11, 21\}$ ,  $T_{diff} = 10.0$ ,  $D_{bh} = 0.040$ ,  $D_{bv} = 0.020$ , static visualization and adaptive orientation). (a) Result for  $n_{dilate} = 0$ . (b) Result for  $n_{dilate} = 1$ . (c) Result for  $n_{dilate} = 2$ .

Li’s work (Li and Xu, 2016) is also aesthetically appealing (Fig. 5b), representing a different woodcut style than ours (since it intends to simulate the Yunnan Out-of-Print woodcut, a tradition Chinese style). We also tested some image processing tools such as Adobe Photoshop and GIMP (Figs 5c and 5d), which did not yield images resembling actual wood carvings.

It should be noted that many of our woodcuts have an appearance similar to typical Brazilian Northeast woodcuts (as Fig. 12, for example), which are

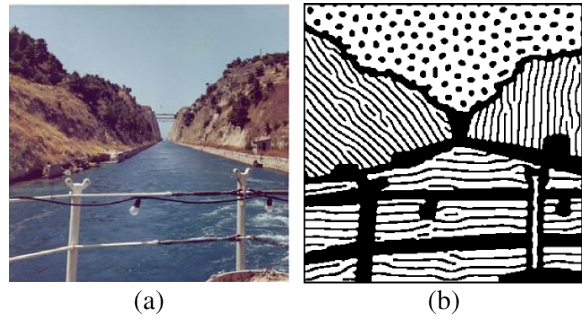


Figure 7: Results from a channel image from the ADE20K dataset. (a) Original image (Zhou et al., 2017). (b) Resulting woodcut.

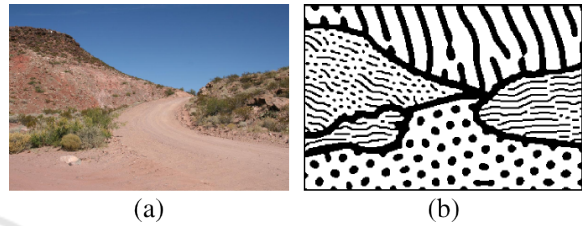


Figure 8: Results from a desert road image from the ADE20K dataset. (a) Original image (Zhou et al., 2017). (b) Resulting woodcut (with  $S_{min} = 0.002$  and  $S_{max} = 0.018$ ).

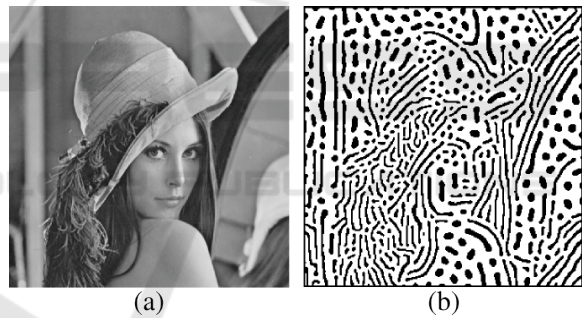


Figure 9: Results using Lenna. (a) Original image. (b) Resulting woodcut (without segmentation, and with  $S$  and  $\theta$  calculated by pixel).



Figure 10: Results from a delicatessen image from the ADE20K dataset. (a) Original image (Zhou et al., 2017). (b) Resulting woodcut (with  $T_{size} = 300$ , adaptive orientation,  $T_{diff} = 10.0$ ,  $D_{bh} = 0.040$ ,  $D_{bv} = 0.020$  and static visualization).

characterized by an abstract form, a black-and-white coloration (including areas with flat black and white color), and the usage of lines and points to express



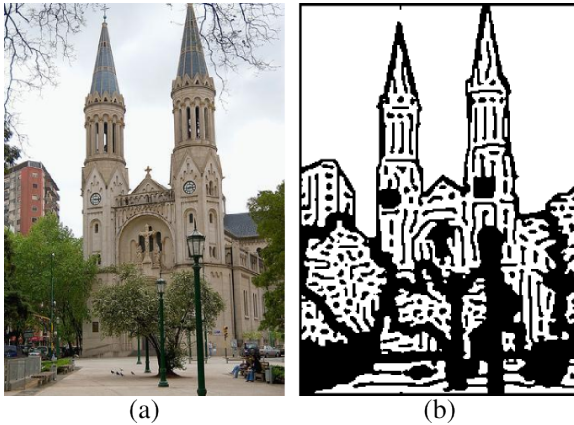


Figure 11: Results from a church image from the ADE20K dataset. (a) Original image (Zhou et al., 2017). (b) Resulting woodcut (with  $\theta$  by pixel,  $D_{bh} = 0.040$ ,  $D_{bv} = 0.020$  and static visualization).

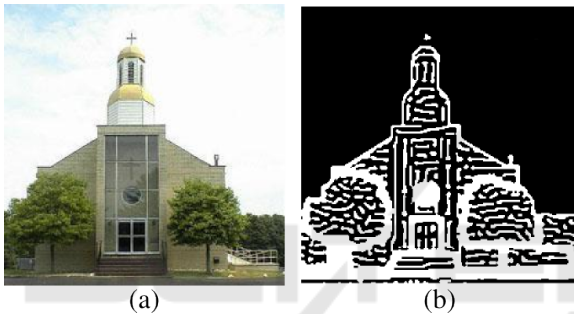


Figure 12: Results from a church image from the ADE20K dataset. (a) Original image (Zhou et al., 2017). (b) Resulting woodcut (with  $\theta$  by pixel,  $D_{bh} = 0.040$ ,  $D_{bv} = 0.020$ , static visualization, and inverted colors).

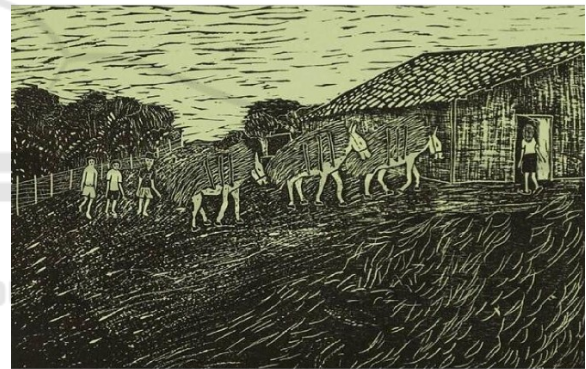
different textures (Fig. 13, for example).

A limitation of our work is that, due to the nature of RD processes as the distribution of chemical substances forming waves of larger or smaller concentration, white and black stripes have more or less the same relative width proportion, so it is not possible to vary the spacing of strokes. Another limitation is the inability to have lines crossing each others (as in the walls of the house in Fig. 13b) In actual woodcuts, strokes are usually more regular than our wave-like stripes, and tend to be longer, without breaking in the middle as sometimes the reaction-diffusion stripes do.

For our simulations, we used an Ubuntu PC with 4 GB of RAM memory and an Intel Core 2 Duo processor (2.80 GHz x2). For Fig. 3(d), for instance, our system took a total of 221 seconds, being 15sec for the preprocessing (mainly for the computation of  $S$  values), 201sec for the RD simulation, and 5sec for post-processing. It should be taken into account that this work is a proof of concept, so our focus was not on code optimization. Also, for many cases, the pat-



(a)



(b)

Figure 13: Actual woodcuts from the Brazilian Northeast Region. (a) (Francorli, 2018), (b) (Gonzaga, 2018).

tern was settled before  $t = 16,000$  iterations. To better analyze the process, the RD system shows the image being generated on real time, which increases the computation burden.

## 5 CONCLUSIONS

We presented a technique to synthesize a woodcut image by using RD. To do that, first we apply a preprocessing step on the input image where we compute information regarding the detail level and the orientation of strokes, generating a parameter map. Then we run a RD system over this parameter map. Last, a post-processing step is done in order to remove noise and binarize the image, resulting into a black and white woodcut, which holds similarity to some styles

of actual woodcuts. Our work shows that RD has a good potential for artistic ends.

To improve our woodcut generating system, we intend to add noise to better simulate the appearance of wood grain in our final woodcuts. Computational efficiency can be improved by setting a stabilization condition for the RD system, so the system will not need to run the entire  $t$  steps after being stabilized into a pattern. Finally, we plan to perform a qualitative evaluation of our woodcut images, to properly validate the quality of our results, using the methodologies described by (Isenberg, 2013).

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