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# Image Blur as a Pictorial Depth Cue

George Mather

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# Image blur as a pictorial depth cue

GEORGE MATHER

*Experimental Psychology, University of Sussex, Brighton BN1 9QG, U.K.*

**SUMMARY**

A range of cues are already known to mediate depth perception in pictures and have been exploited by artists in drawings and paintings. Modern images are commonly generated by photographic or video equipment, and these images contain a depth cue that cannot be found in artistic depictions of natural scenes: different image regions are often blurred by different amounts, because of depth of focus limitations. Demonstrations presented here show that this selective image blur also acts as a pictorial depth cue, even when other pictorial cues are removed. Experimental data indicate that the degree of blur at borders between blurred and sharp image regions is used by the visual system to establish the depth ordering of different regions. Selective image blur is thus a potentially useful addition to computer-generated and cartoon images to enhance the impression of depth they convey. It may well also contribute to depth perception in natural retinal images, because the depth of focus of the human eye is limited.

## 1. INTRODUCTION

Although the eyes receive flat, two-dimensional images of the world, we experience a rich, vivid impression of three-dimensional space. A range of visual cues allow accurate judgements to be made about the relative depths of objects in the scene. Binocular cues arise from the slightly different views of the world provided by two adjacent forward-facing eyes. There are also a number of pictorial cues to depth, so-called because they have been used for centuries by artists to depict realistic three-dimensional scenes in drawings and paintings. These cues include perspective (the convergence of lines as they recede into the distance), relative size, and interposition (partial occlusion of objects in the scene by nearer objects; for a discussion of pictorial depth cues in art, see Solso 1994). Modern pictorial images are very often generated by video and photographic equipment, and it will be argued in this paper that a new depth cue is available in such images, in addition to the pictorial cues traditionally exploited by artists. It will be demonstrated that image blur makes a significant contribution to perception of depth relations in photographic images, and may also contribute to the depth seen in natural retinal images.

Figure 1 shows two views of the same scene, containing a small foreground object against a patterned background. On the right, all parts of the scene appear in sharp focus, but on the left only the foreground object is sharply defined. The application of blur to the background enhances the impression of depth, so that sharply defined regions appear to stand forward of blurred regions. Striking effects of this kind can often be found in photographs on the sports pages of newspapers. Action photographs tend to be taken with long telephoto lenses and wide apertures, maximising the blur of the background (usually containing spectators) while the performers remain in sharp focus. Of course, a number of cues contribute to pictorial depth perception, including object knowledge, shading, occlusion, and relative contrast. Several such cues are available in figure 1. However, it is not clear why selective blur should enhance these depth-separation cues, because it has the contrary effect of obscuring them (eg. removal of occlusion detail in background objects). Rather than modulating other cues, it will be argued here that blur itself can act as a pictorial depth cue.

### (*a*) *Image blur as a depth cue in random dot images*

The synthetic images in figure 2 demonstrate that blur is an effective depth cue even when other pictorial cues are removed. The lefthand image was generated by computer from a dense field of random black–white elements. All except a small square region of texture elements were blurred by the computer. The sharply defined region appears to float above the blurred background. It could be argued that the apparent depth seen in the figure is caused by cues resulting from occlusion of blurred blobs by the sharp region, or from the lower average contrast of the blurred region. The righthand image contradicts these explanations. The background is identical to that in the lefthand image, except that graded variations of intensity have been quantized to just two levels: light grey and dark grey. The surrounding region still contains blob shapes, and has the same average contrast as in the lefthand image, but no longer appears blurred. There is little, if any depth effect.

In the lefthand image of figure 2, blur was applied selectively to one region of texture and not to the other, but in natural images blur can arise at boundaries

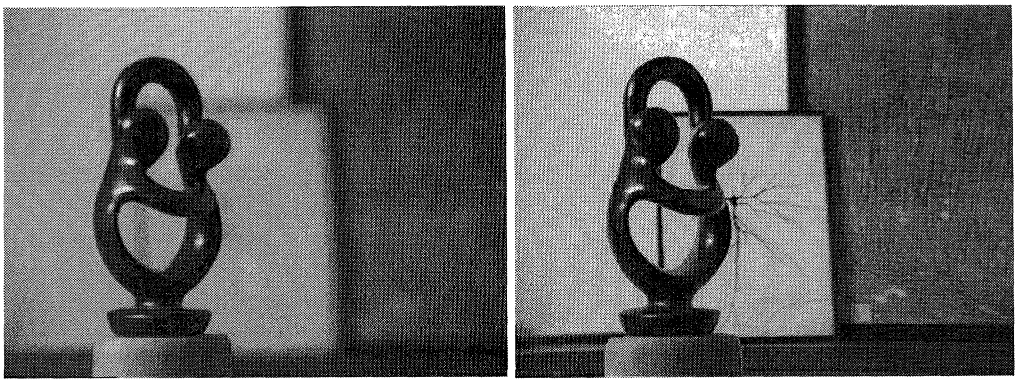

Figure 1. Two views of a small sculpture. On the left, background detail is blurred, and on the right it is sharply defined. The apparent separation in depth between foreground and background is influenced by image blur, so that the appearance of depth is greater in the lefthand than in the righthand image.

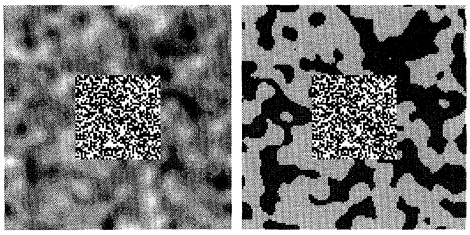

Figure 2. Blur as a pictorial depth cue in computer-generated random dot images. In the lefthand image, all except a small square region of black–white texture was blurred by application of a Gaussian blurring function (space constant equal to three element widths). Sharp and blurred regions were normalised to the same peak contrast. The central square appears to float above the background. The righthand image is identical to the lefthand image, except that intensities in the background have been quantised to just two levels: all points of below-average intensity were set to dark grey, and all points with intensity above average were set to light grey. The background no longer appears blurred, and the depth effect is poor despite the persistence of occlusion cues.

between shapes as well as within shapes. Figure 3 demonstrates that contour blur can also lead to an impression of depth.

It shows a series of images in which two uniformly dark rectangles are superimposed on a blurred random pattern. The border of the upper rectangle is itself blurred, but the border of the lower rectangle is sharp. The degree of blur in the upper rectangle increases from left to right across the sequence.The lower rectangle appears nearer than the upper, and the degree of apparent depth separation between the rectangles depends on the degree of blur in the upper rectangle.

### (*b*) *Region blur and border blur as a cue in figure-ground segregation*

Blurred regions in real-world images arise because objects in those regions lie outside the imaging system's zone of focus, either too near or too far away. The border between blurred regions and sharper regions can be used to establish the relative depth of different regions. If the border is itself blurred, then it must be attached to the blurred region, which must therefore be nearer. If the border is sharp, then it cannot be attached to the blurred region, and must therefore belong to an object that is nearer than the blurred region.

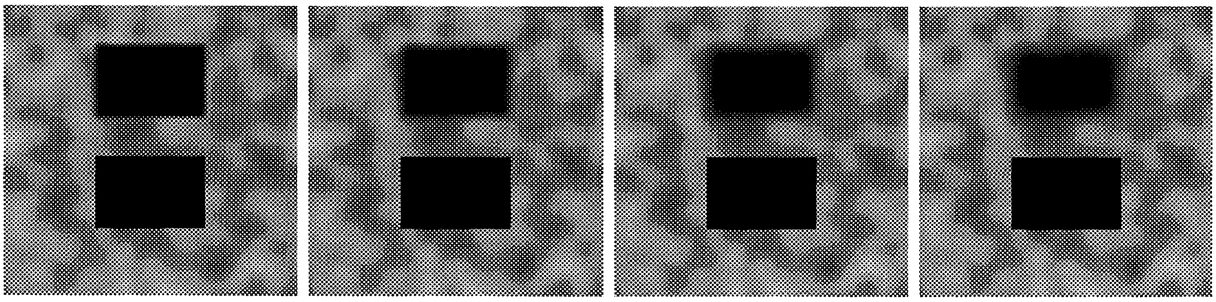

Figure 3. Each image in this sequence shows two dark rectangles of equal size and intensity superimposed on a blurred random texture. The edges of the upper rectangle are also blurred, whereas the edges of the lower rectangle are sharp. The background texture is a 128 × 128 element array of random black–white dots, blurred using a Gaussian function with a space constant equal to four dot widths. The Gaussian space constant applied to the upper rectangle was equal to one dot width in the leftmost image, then two, three, and four element widths reading from left to right across the remaining images. The lower rectangle appears nearer than the upper rectangle, and the degree of apparent depth separation between the rectangles depends on degree of blur, so that they appear closer together in the leftmost image than in the rightmost image.

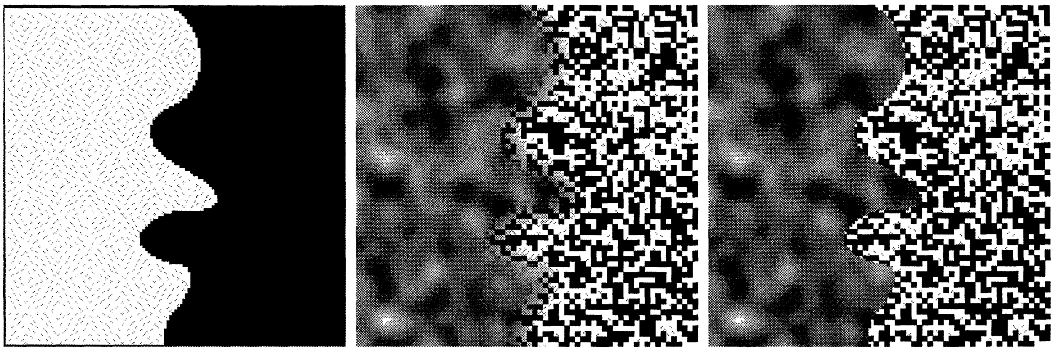

Figure 4. Blur as a cue in figure–ground segregation. The lefthand image illustrates classical figure–ground ambiguity: either the light area or the dark area can be seen as a 'figure' to which the curved border is attached. In the other two images, the light area has been filled with blurred texture, and the dark area has been filled with sharp texture at equal mean luminance and contrast. In the middle image the border between the two is blurred, and in the righthand image the border is sharp. Results confirmed that the blurred region is usually judged as nearer in the middle image, but farther in the righthand image, as expected if both region and border blur are taken into account when making depth judgements.

To investigate whether human observers can exploit information about region and border blur when making depth judgements, an experiment was done using ambiguous figure–ground stimuli.

The lefthand image in figure 4 is a classical ambiguous figure: the border separating the dark and light regions can be perceived as belonging to either region. The region to which the border is attached is seen as figure, and the other region is seen as background (Woodworth & Schlosberg 1954). New versions of this figure were created, in which the two regions differed only in terms of texture blur, and the border between the two regions was either blurred or sharp. Two examples are illustrated on the right of figure 4. In both, the region on one side of the figure contains sharply defined texture and the region on the other side contains blurred texture. In one image, the border between sharp and blurred regions is itself sharp, and in the other the border is blurred. If border and region blur can be used together in depth judgements, then observers should perceive the blurred region as nearer when the border is blurred, but should perceive the sharp region as nearer when the border is sharp. The two textured images in figure 4, and two others in which blurred and sharp textures exchanged places, were shown to six subjects ten times each, one after the other in random order on a computer monitor. Each image subtended $9.75 \times 11.5$ deg. arc, and had a mean luminance of 37 cdm$^{-2}$ and contrast of 0.88. Each presentation lasted two seconds, after which the subject reported which side of the figure appeared nearer than the other by pressing a mouse button.

On average, the blurred region was perceived as nearer in 96.7% of presentations when the border was blurred (S.E. 3.3%), but it was perceived as nearer in only 19% of presentations when the border was sharp (S.E. 10%). This difference is highly significant ($t = 8.8$; d.f. $= 5$; $p < 0.001$). We conclude that image blur both in regions and at borders can be used when making depth judgements.

## 2. DISCUSSION AND CONCLUSIONS

Selective image blur is very common in photographic and video images, because of technical limitations on depth of focus, and these demonstrations and data support the view that it makes a significant contribution to the impression of depth conveyed by such images, independently of other pictorial depth cues. The realism of computer-generated and cartoon images of naturalistic scenes should also be enhanced by the addition of selective blur to background regions. Indeed, many modern cartoon-animation films already incorporate blur effects.

Blur is also a potential cue in natural retinal images, because the depth of focus of the human eye is limited. Psychophysical measurements (Campbell 1957) estimate it to be +/− 0.3D with a 3 mm pupil under conditions of high illumination. So, if the eye were focused on a point 100 cm from the observer, other points in the visual scene nearer that 77 cm and farther than 140 cm would be perceptibly blurred to a degree that depends on distance. Psychophysical experiments by Watt & Morgan (1983) and by Georgeson (1994) indicate that human observers are very sensitive to small differences in image blur. Georgeson (1994) also proposed a biologically plausible model for the extraction of blur, based on responses from receptive fields that perform local spatial differentiation. Thus the visual system appears to possess machinery that provides precise measurements of image blur. The work presented here demonstrates that these measurements play a role in the perception of depth.

I thank Linda Murdoch and Andrew Daniell for assistance with data collection. The images used in figure 1 were digitized and processed using *NIH Image* software on a Macintosh computer.

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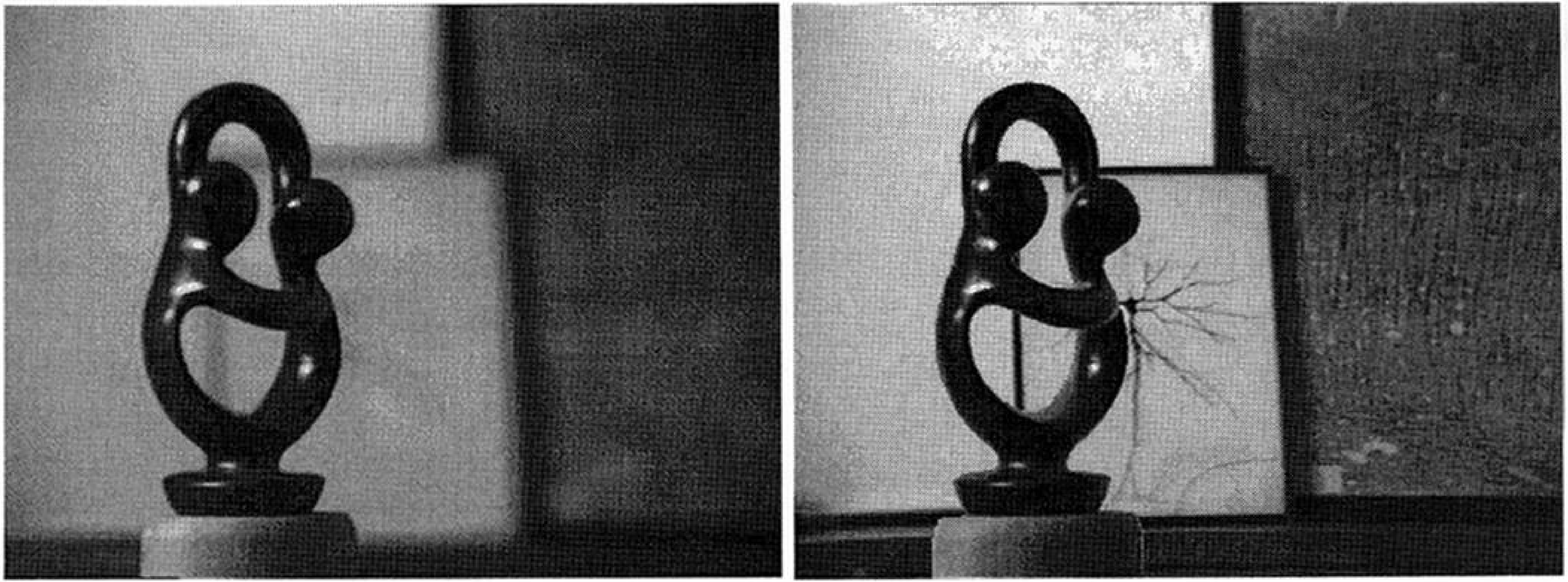

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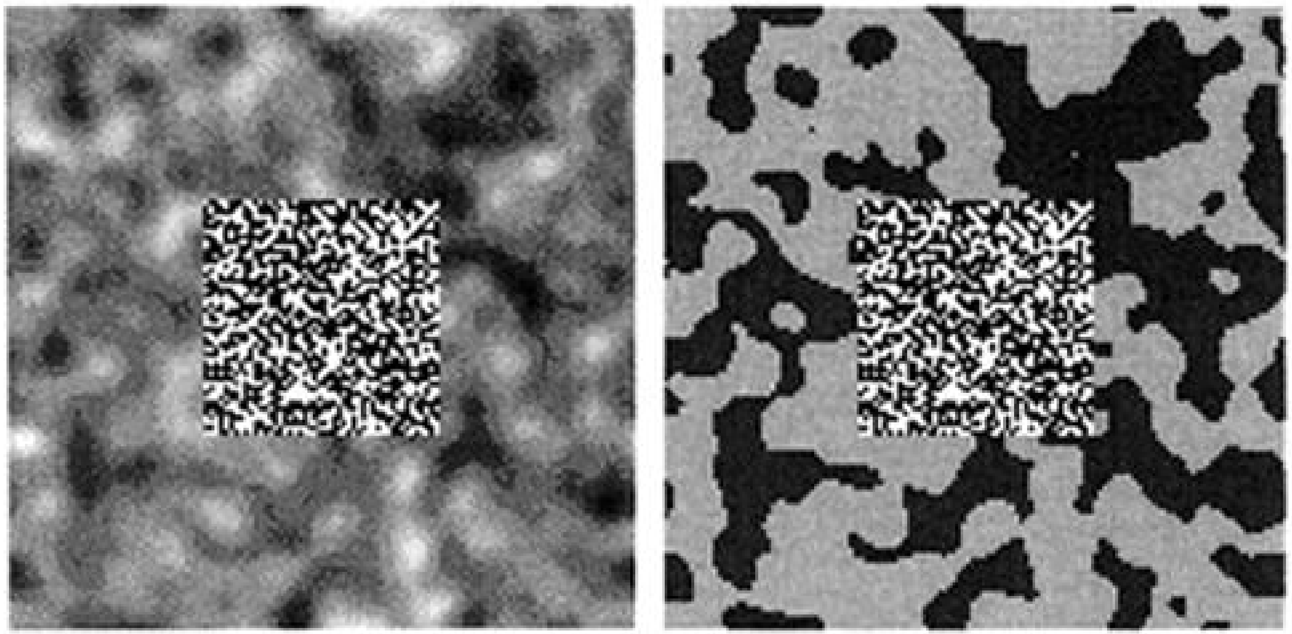

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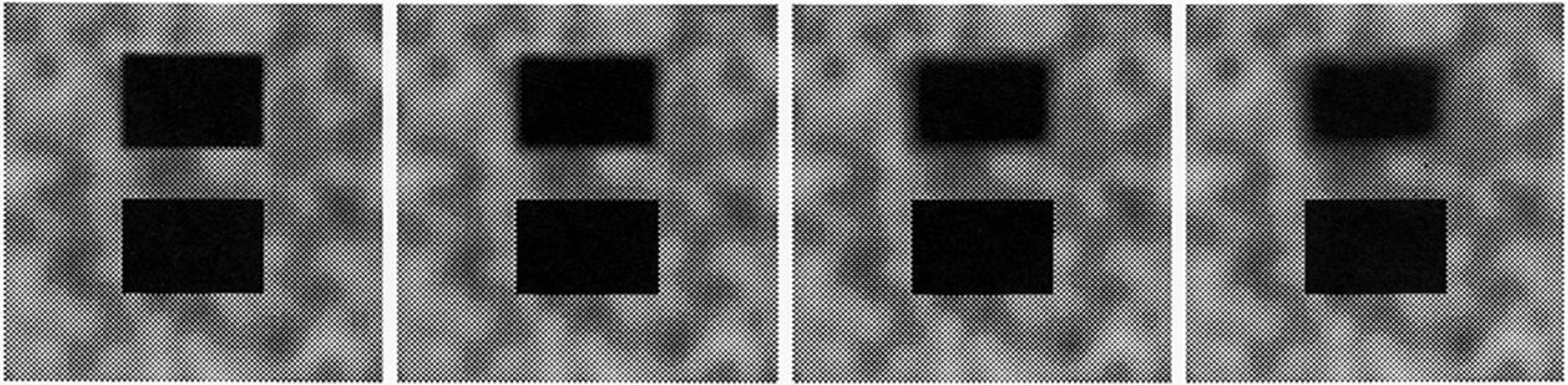

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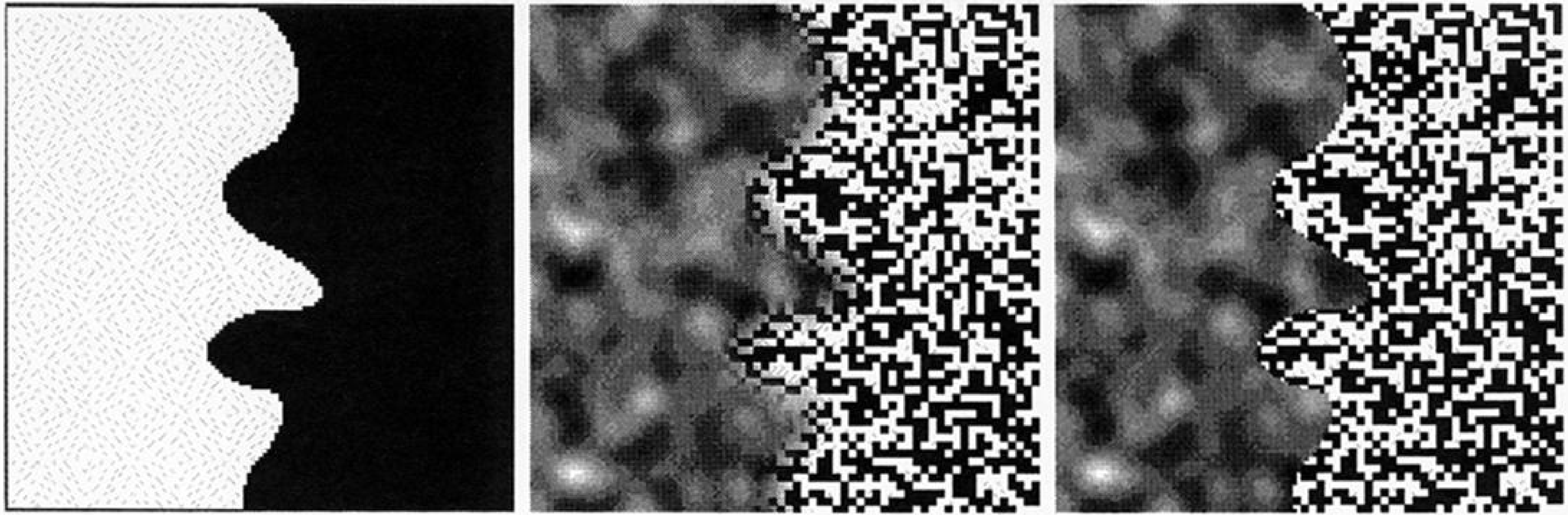

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