Fundamental Properties of Digital Images[1]

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The quality of a digital image is affected by matrix size, unsharpness in the underlying image, bit depth, and noise in the underlying image. The array of all of the pixels into which an image is divided is the image matrix. If the image matrix is small (ie, composed of a few large pixels), the resolution of the digital image is low. Image blur dominates when the pixel size is much smaller than the unsharpness of the underlying image. The density in a pixel is represented by a binary number with a variable number of bits (bit depth). The more noise present in the initial image, the fewer the bits that are needed to convey its representation. Insufficient numbers of bits in the digital representation of an image, whether from too few pixels or too small a bit depth in each pixel, result in inadequate image quality. Use of too many bits, relative to the quality of the underlying image, places an increasingly unwarranted demand on digital image handling and processing.

■ INTRODUCTION

An increasing fraction of radiologic images are handled in digital format. Image quality is affected by matrix size, unsharpness in the underlying image, bit depth, and noise in the underlying image. This article is a systematic visual review of the influence of these fundamental parameters on the appearance of digital images.

The starting point of this review is the image of a seascape shown in Figure 1. This type of image is called an *analog* image because its continuous distribution of density represents the continuous distribution of light intensity in the original scene. This image was selected because it includes important features similar to those found in clinical images. The lighthouse tower illustrates resolution effects, particularly the windows and the details of the light itself. The sky illustrates contrast and noise effects. The rocky foreground exhibits interactions between resolution, contrast, and noise.

Index terms: Images, display • Images, quality • Physics • Radiography, digital

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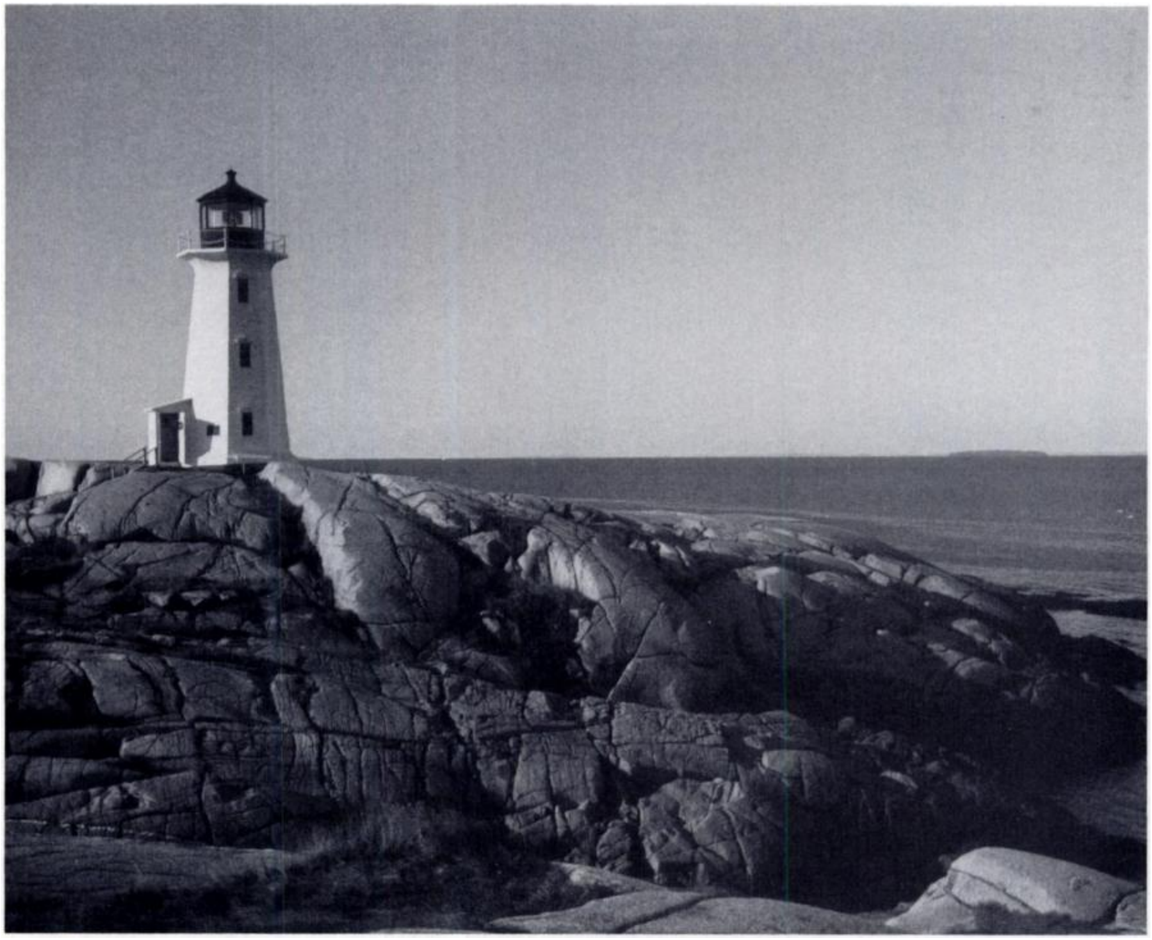


Figure 1. Analog photograph of the lighthouse at Peggy's Cove, Nova Scotia. The original image was photographed with color negative film.

■ SPATIAL SAMPLING

The analog image can be converted into digital form or digitized. The process begins by dividing the image into a number of boxes as shown in Figure 2. This process is called *spatial sampling.* Each of these boxes is called a *pixel.* The array of all of the pixels into which the image is divided is called the *image matrix.* The image shown in Figure 2 is divided into four large pixels. This image matrix has two rows and two columns of pixels; thus, it is a 2 × 2 matrix or a 2^2 matrix. If we divided the image into 1,024 rows and 1,024 columns of pixels, it would be a 1,024 × 1,024 matrix. Most digital radiologic images have matrix sizes ranging from 256 × 256 to 2,048 × 2,048, with 512 × 512 and 1,024 × 1,024 being the most common.

Each pixel is filled with a uniform density. The average density of the structures within a pixel determines its gray value.

If the image matrix is composed of a few large pixels, few of the details in the original image will be visible. As each individual pixel is made smaller, more of the original image

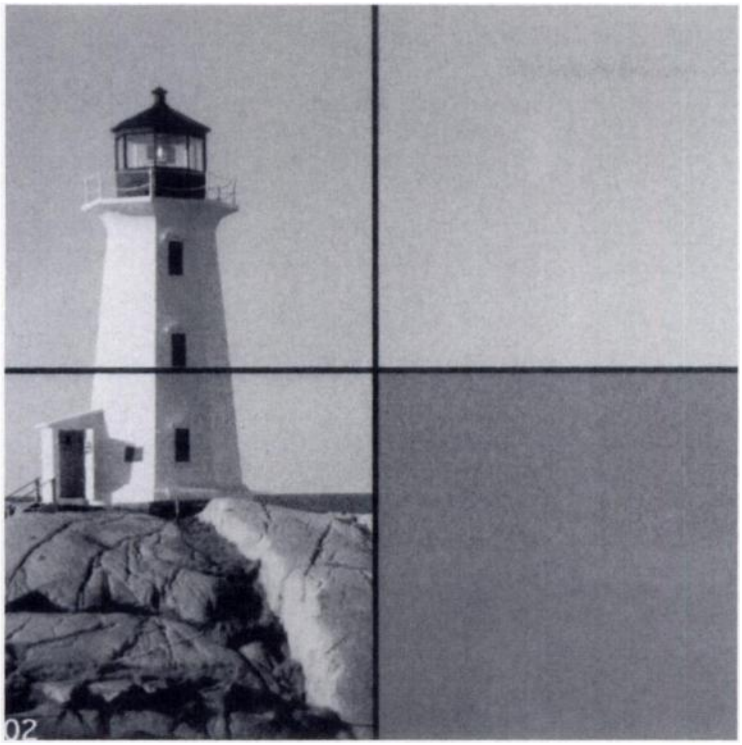
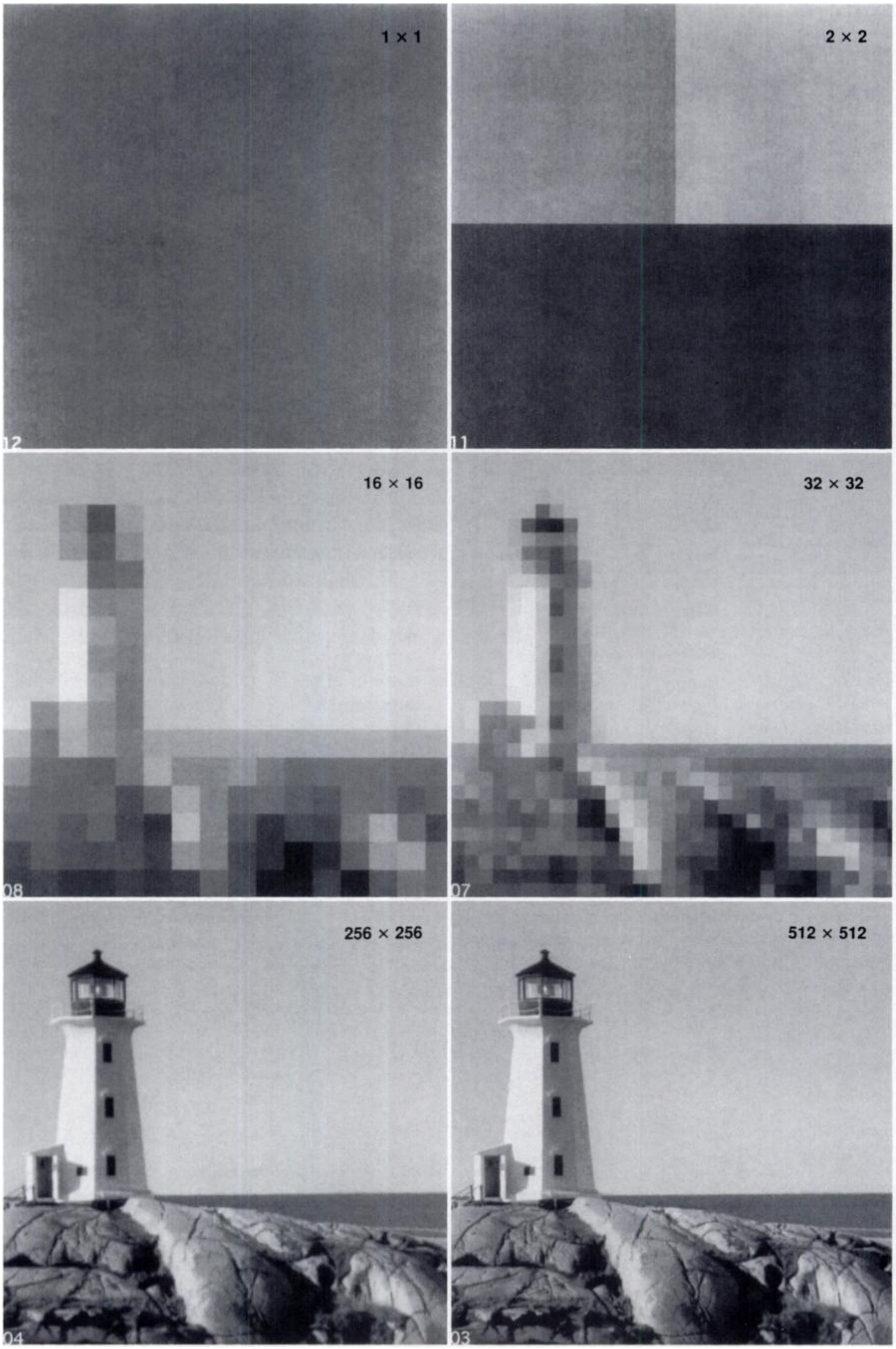
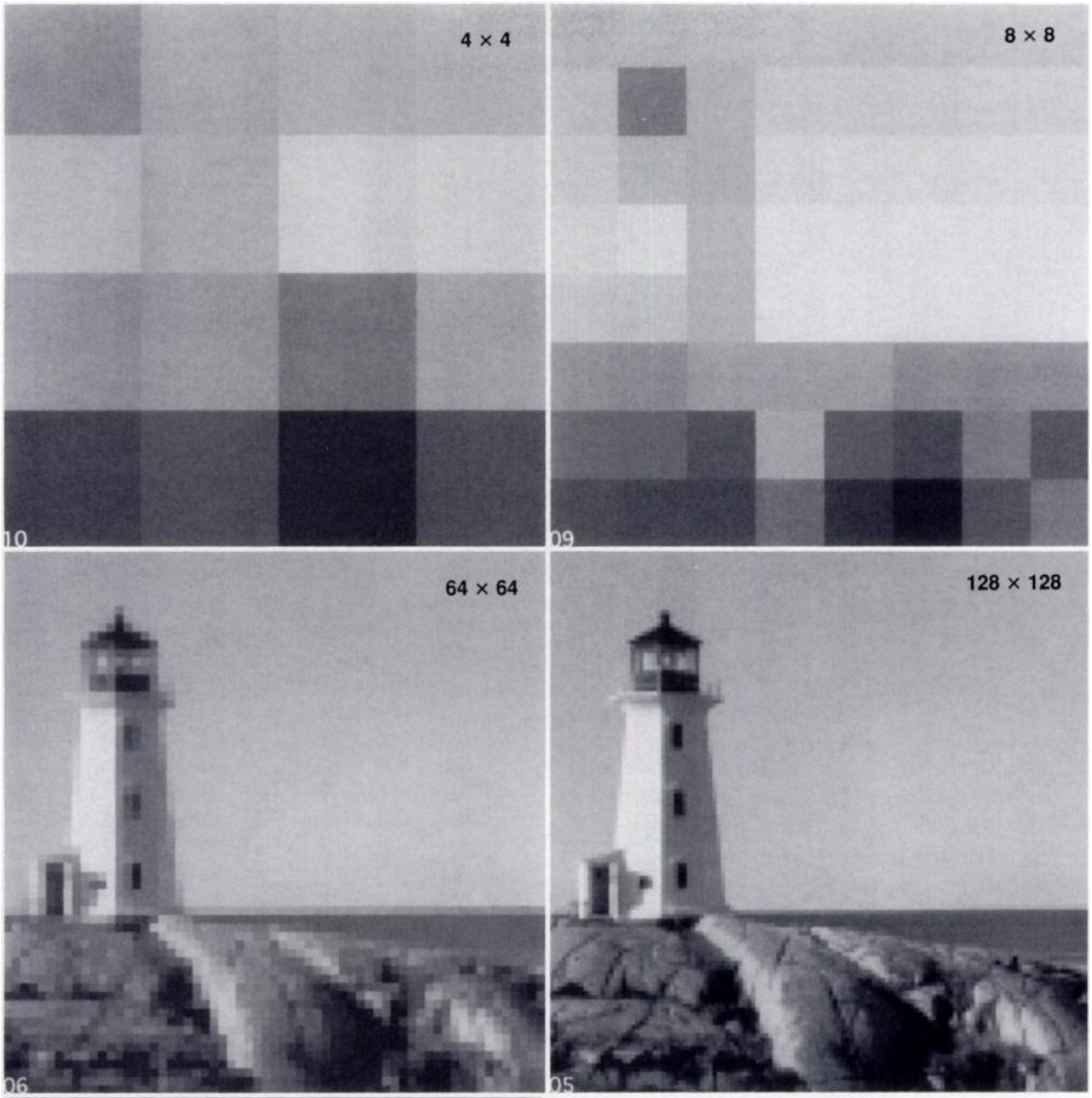


Figure 2. The digitization process begins by dividing the image into a number of regions called pixels (here, four), which are each filled with a single density. The lower right pixel is uniformly filled with the average density of the corresponding region of the original image.

detail becomes visible. This is illustrated in Figure 3. As the pixel size decreases, the total number of pixels increases rapidly. Although use of too few pixels degrades the resolution of the image, too many pixels may be impractical. For the usual square image matrix, the total number of pixels quadruples every time the width of a pixel is divided in half. More pixels require more storage space in the computer and slow the passage of a complete image through an image processor or to a display device.

The total number of pixels needed to portray an image is determined by both the size of an individual pixel and the size of the entire image. Many more pixels are required to represent a large image at any given resolution than the number needed for a small image. The size of each individual pixel determines the resolution of the image. The total number of pixels multiplied by the pixel size determines the *field of view.* Conversely, if the matrix size is fixed, image resolution will decrease as the field of view is increased. Figure 4 is an example of two 128 × 128 matrices. As the size of each pixel is increased, the field of view increases and the resolution decreases. It would take 64 times as many pixels to represent the entire scene if the pixel size in the insert were used for the entire field of view. For example, the last image seen in Figure 3 contains 1,048,576 pixels.


1 × 1
2 × 2
16 × 16
32 × 32
256 × 256
512 × 512



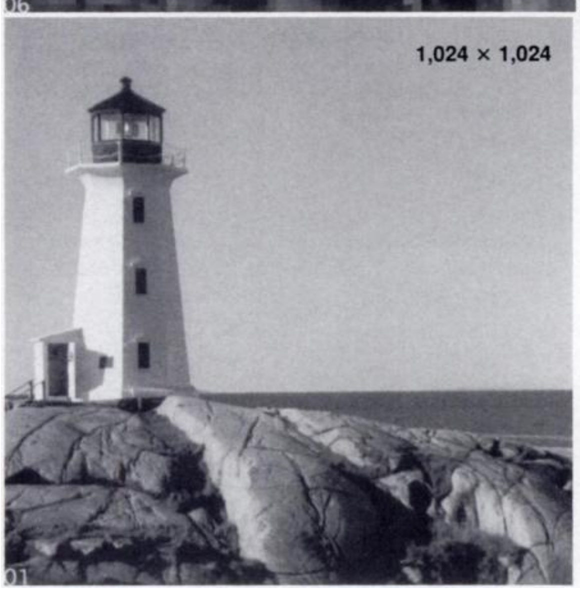


Figure 3. The analog image has been reproduced in several digital matrices, ranging in size from 1 × 1 to 1,024 × 1,024. The uniform density in each pixel is the average density of the corresponding region of the original image. Note that pixel boundaries are very sharp, even when there is no detail remaining from the underlying image.

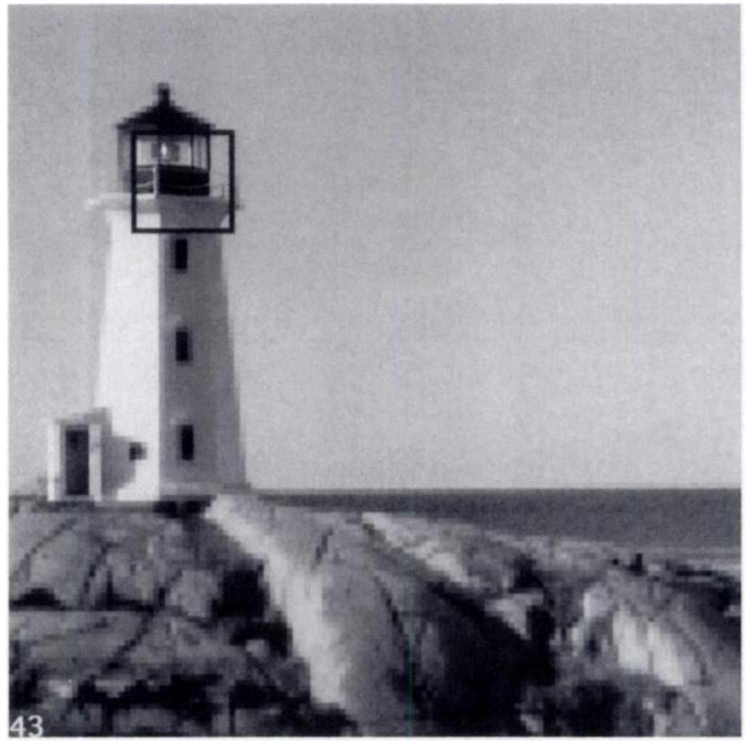


Figure 4. The entire image has been digitized to a matrix size of 128 × 128. Each pixel is 8 units wide (eight times the width of one of the original pixels.) The small insert near the light is also digitized to a matrix size of 128 × 128 with 1-unit wide pixels. The total number of pixels in the entire picture (16,384) and in the small insert is the same. High resolution and a large field of view require a tremendous number of pixels.

The original analog image may have limited spatial resolution or *sharpness* for a variety of reasons. The size of individual pixels should be based on the resolution of the underlying analog image. Figures 5 and 6 illustrate this point clearly. In Figure 6, the initial image was electronically blurred to different degrees as shown in the left-hand column. The influence of pixel size at each degree of blurring is shown in the rows of constant pixel size. Initially, the visibility of details in the blurred image improves as the pixel size decreases. This is because the blurring due to the digitization process is greater than the underlying unsharpness of the image. Once the pixel size becomes significantly smaller than the blur in the image, further reductions in pixel size (larger matrices) do not yield any further improvements in the visibility of image details.

Blur Radius					
No Blur	P11	P12	P13	P14	P15
2	P21	P22	P23	P24	P25
4	P31	P32	P33	P34	P35
16	P41	P42	P43	P44	P45
32	P51	P52	P53	P54	P55
Original Matrix Size	1024	512	256	64	16
Pixel Width	1	2	4	16	64

Figure 5. Index to the variations in blur, image matrix size, and pixel width used to produce the images seen in Figure 6. The numbered cells in the array correspond to the numbered images.

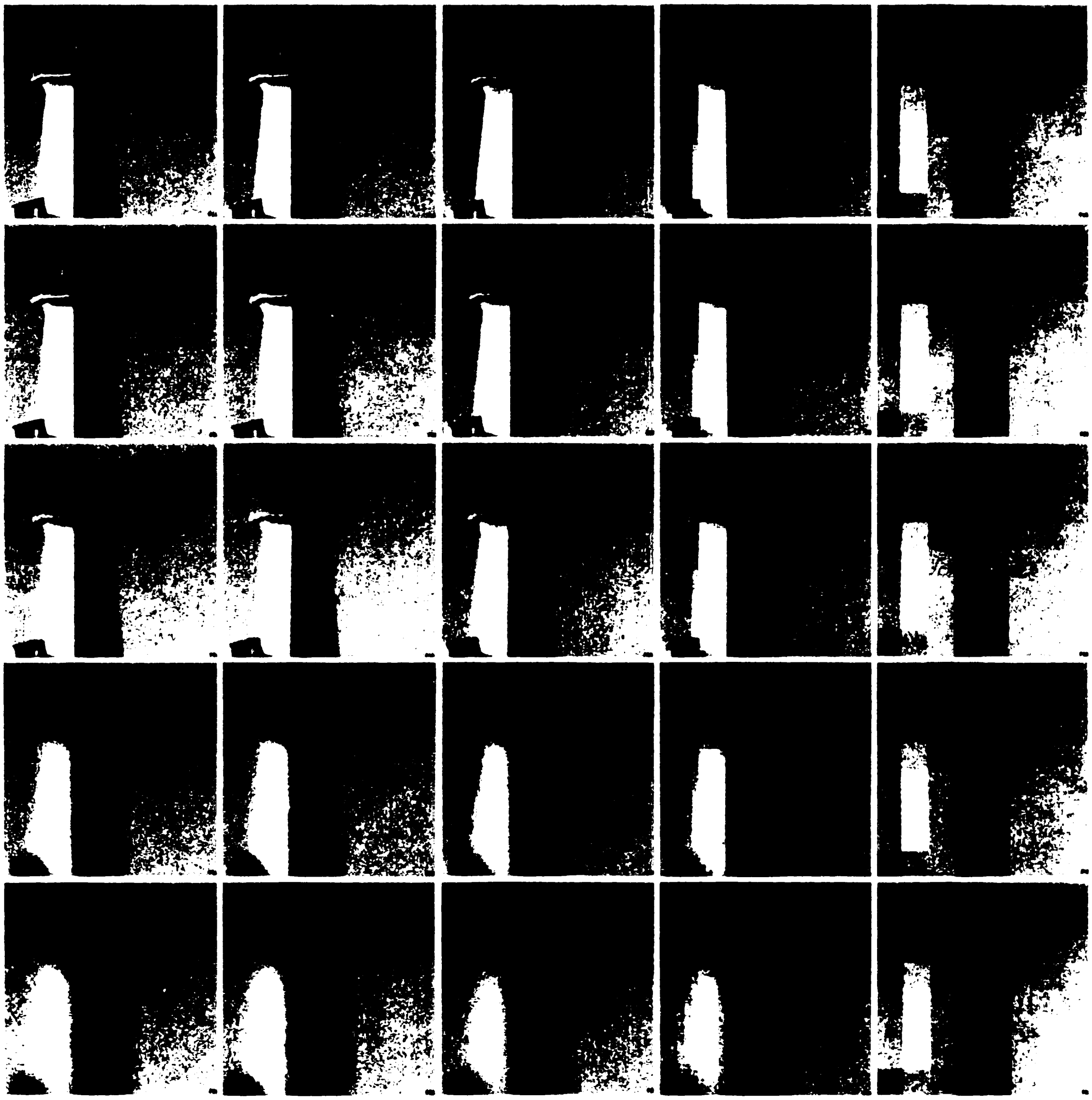


Figure 6. Digital images demonstrate the interrelated effects of image blur and matrix size on the visibility of detail. Each row has the same degree of blur in the underlying image; each column has the same matrix size. Image blur dominates when the pixel size is much smaller than the unsharpness of the image. Pixel effects dominate when the pixel size is much larger than the unsharpness of the image. Both effects play a role when blur and pixel size are of comparable dimensions.

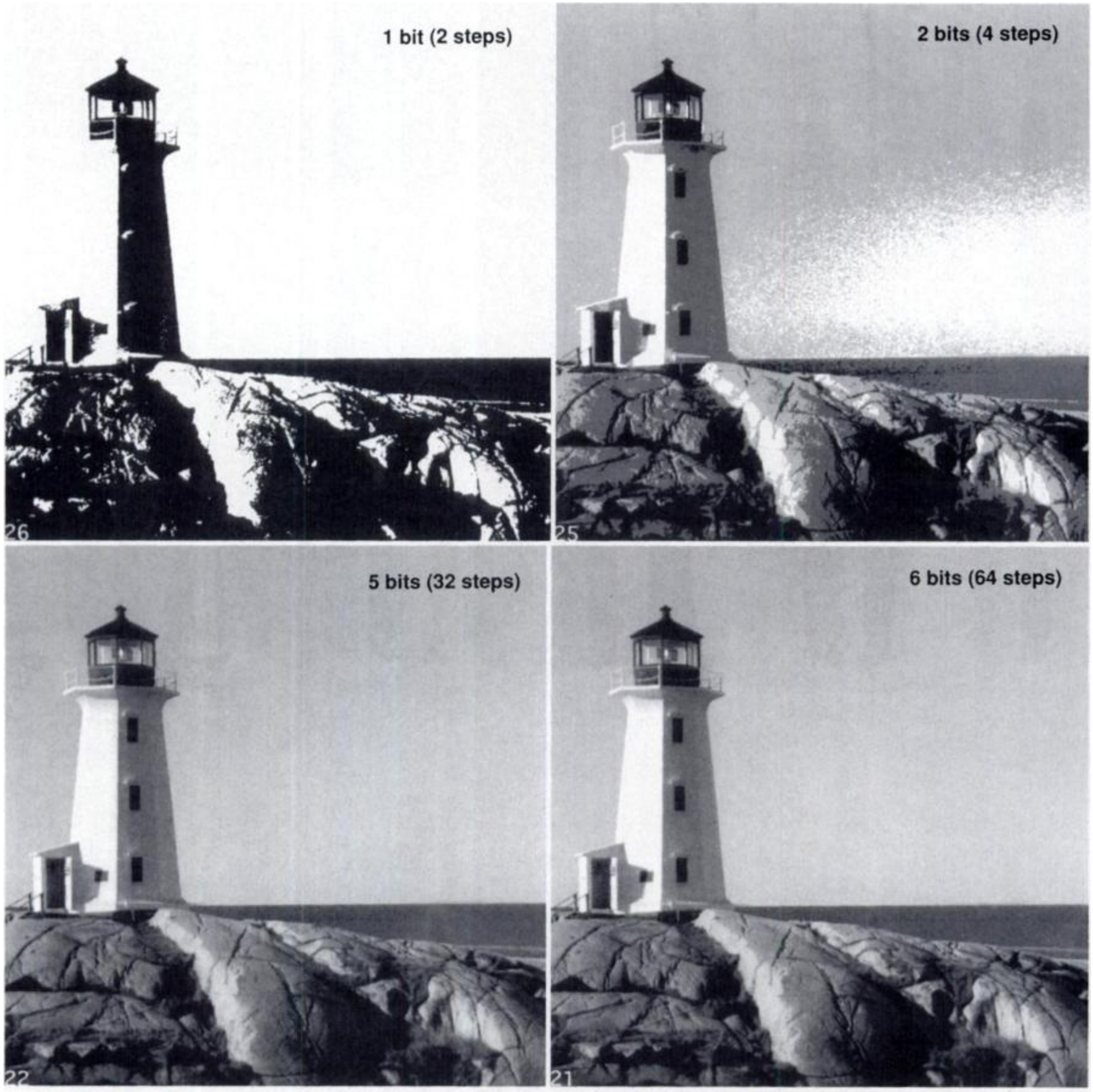
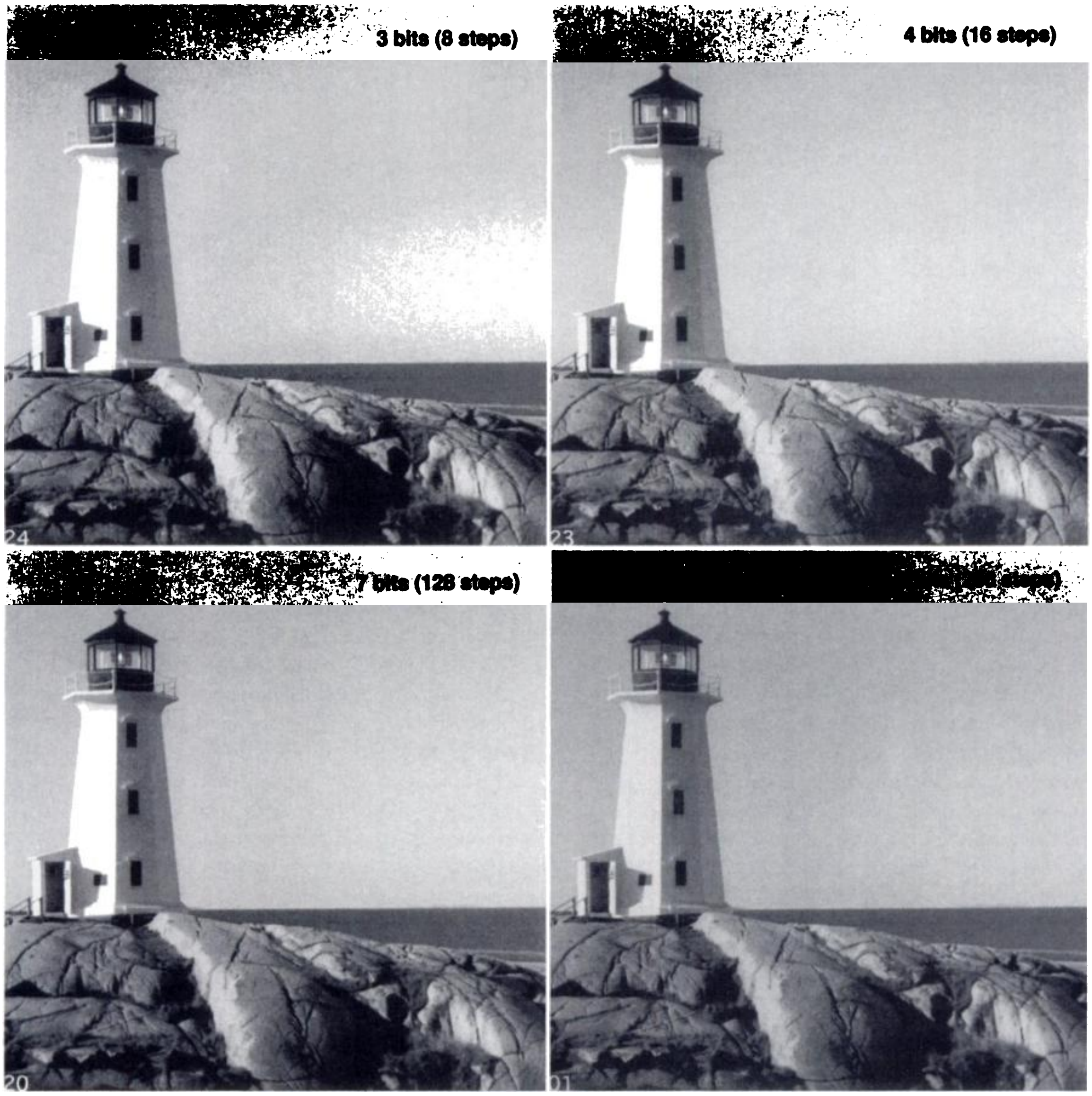


Figure 7. Images demonstrate the effect of bit depth on image quality. Use of too few steps causes the "clouds" seen in the 2-, 3-, and 4-bit images. These are artifactual contours produced by insufficient bit depth.

■ CONTRAST RESOLUTION

In the foregoing discussion of spatial sampling, we assumed that any value can be assigned to the density within any given pixel. The density in a digital image is actually represented by a binary number. An ***analog-to-digital converter*** transforms the original continuous density into a set of discrete gray levels. This process is called digitization. All gray levels similar in value to one of these steps are transformed into exactly the gray level of that step. It is possible to use a few or many steps between black and white. The number of



available steps or gray levels is determined by 2^N, where N is the number of bits (often called bit depth) in the binary number used to represent the density in each pixel. The digital representation of the density in each pixel ranges from 1 bit (black or white) to 8 bits (256 steps between black and white). The difference in density between adjacent steps is called the *contrast resolution* of the image.

Figure 7 illustrates the effects of bit depth on the appearance of an image. If too few steps are used, there will be a noticeable difference in density between adjacent steps. This leads to the production of artificial contours (ie, *contouring*) in the image.

Added Noise (bits)					
None	N11	N12	N13	N14	N15
1 - 0.8%	N21	N22	N23	N24	N25
3 - 3.1%	N31	N32	N33	N34	N35
5 - 12.5%	N41	N42	N43	N44	N45
7 - 50%	N51	N52	N53	N54	N55
Bit Depth	8	7	5	3	1
Gray Steps	256	128	32	8	2

Figure 8. Index to the variations in image noise, bit depth, and gray steps used to produce the images seen in Figure 9. The numbered cells in the array correspond to the numbered images.

■ NOISE

Each analog image has an intrinsic contrast resolution as well as an intrinsic spatial resolution. Image noise limits the contrast resolution of a picture. Although noise is most easily seen in uniform areas, it is present everywhere in the image. It serves no useful purpose to use more bits to digitize the density in a pixel than are justified by the noise content of the original image. This is illustrated by the sequences shown in Figures 8 and 9. Specific amounts of statistical noise have been added to the starting image in each sequence, before bit depth is reduced. Several effects may be seen in this array of images. If one compares the images in each sequence, it is obvious that the more noise present in the initial image, the fewer the bits that are needed to convey its representation. Differences in image quality as a function of bit depth are visible in the noise-free top row. As noise is added, the differences between 8-, 7-, 5-, and 3-bit representations become unnoticeable. Finally, there is almost no difference in image quality in the 8-bit and 1-bit versions of the extremely noisy images in the bottom row.

Random noise fluctuations mask the contouring caused by insufficient bit depth. This is most easily seen by comparing the 3-bit images at different noise levels. The effect is barely visible in the 5-bit column.

A conceptual paradox can be clearly seen in the 1-bit images of Figures 8–11. When noise is added to an image *before* digitization, more information is carried in this representation than in the digitized noise-free image. The more noise present at a point in the image, the more likely it is that the value of signal plus noise in that pixel will cross a gray-scale step boundary and be distinguishable from its surroundings. Perhaps, in this manner, ultrasonic speckle noise contributes to the visibility of anatomic structure. The effect shown in Figure 11 is similar to the "structured noise"

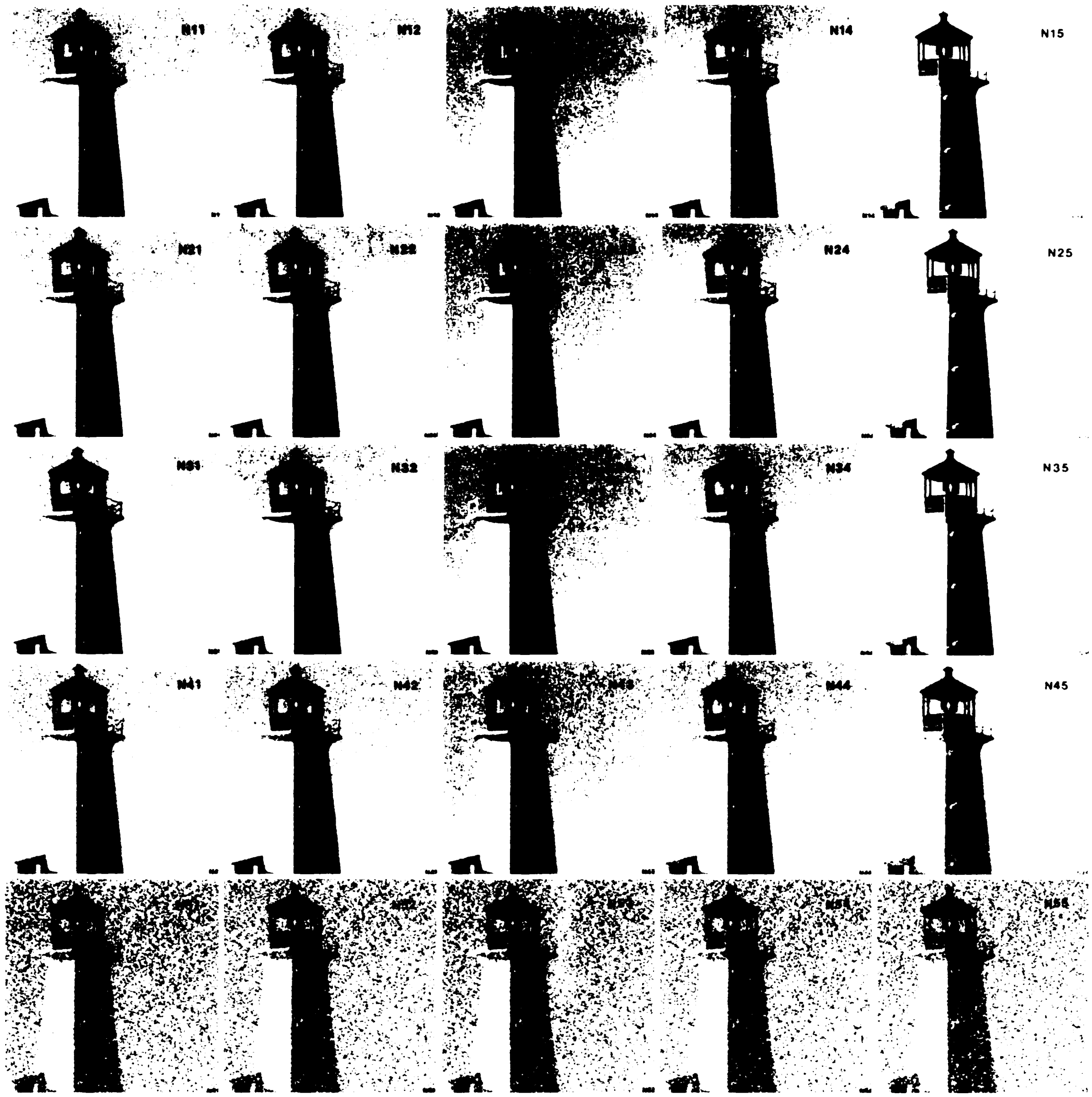


Figure 9. Images demonstrate visibility of objects. Each row has the same amount of noise added to the underlying image. Each column has the same bit depth. (See the text for detailed discussion.)

added in the printing process with the use of half-tone screens. In fact, all of the images in this journal are actually 1-bit representations of the original materials.

■ SUMMARY

This article has pictorially reviewed some fundamental aspects of unsubtracted digital images. Image quality clearly is affected by both matrix size and bit depth. Insufficient numbers of bits in the digital representation of an image, whether from too few pixels or too small a bit depth in each pixel, result in inadequate image quality. Use of too many bits, relative to the quality of the underlying image, places an increasingly unwarranted demand on digital image handling and processing technology. There is an interesting amorphous gray area in which intrinsic image qual-

No added noise	G 07 2.7%	G 10 3.9%
G 14 5.5%	G 20 7.8%	G 28 10.9%
G 40 15.6%	G 56 21.9%	G 80 31.3%
G 110 43.0%	8 bit reference	

Figure 10. Diagram depicts the percentage of noise that was added to the images seen in Figure 11. The numbered cells correspond to the numbered images.

ity, digital parameters, and the observer's ability to extract necessary information from a scene all play a role. Diagnostic image quality in the digital domain is no easier to define than it is for analog images.

■ APPENDIX

The original image was obtained with Kodacolor 100 film (Eastman Kodak, Rochester, NY). A portion of the negative was digitized with a matrix size of 1,024 × 1,312 pixels. The digitization process converted the image from an analog color to an 8-bit gray-scale format. The digital image was processed with Photoshop (Adobe Systems, Mountain View, Calif). The gray scale was uniformly stretched until the density range of the image filled all 8 available bits. The image was then digitally cropped to 1,024 × 1,024 × 8 bits (last image in Fig 3). The lower digital resolution images in Figure 3 were produced by averaging the brightness values in appropriate-sized regions of the master image. The blurred images in Figure 6 were produced by applying gaussian blur functions of indicated size to the master image before the matrix size was reduced. The lower bit depth images in Figure 7 were produced by grouping adjacent densities in the master image and using the Posterize filter in Adobe Photoshop. Gaussian noise was digitally added to the master image before the bit depth was reduced in Figures 9 and 11. Producing the large number of images needed for this article was not a trivial exercise. It proved impossible to obtain the same gray scale by using ordinary photographic techniques. The prints that were used for publication were made with a thermal dye diffusion printer (XL7700; Eastman Kodak). Adobe Photoshop was used to digitally drive the printer. There was a one-to-one correspondence between pixels in the digital image and printer pixels.

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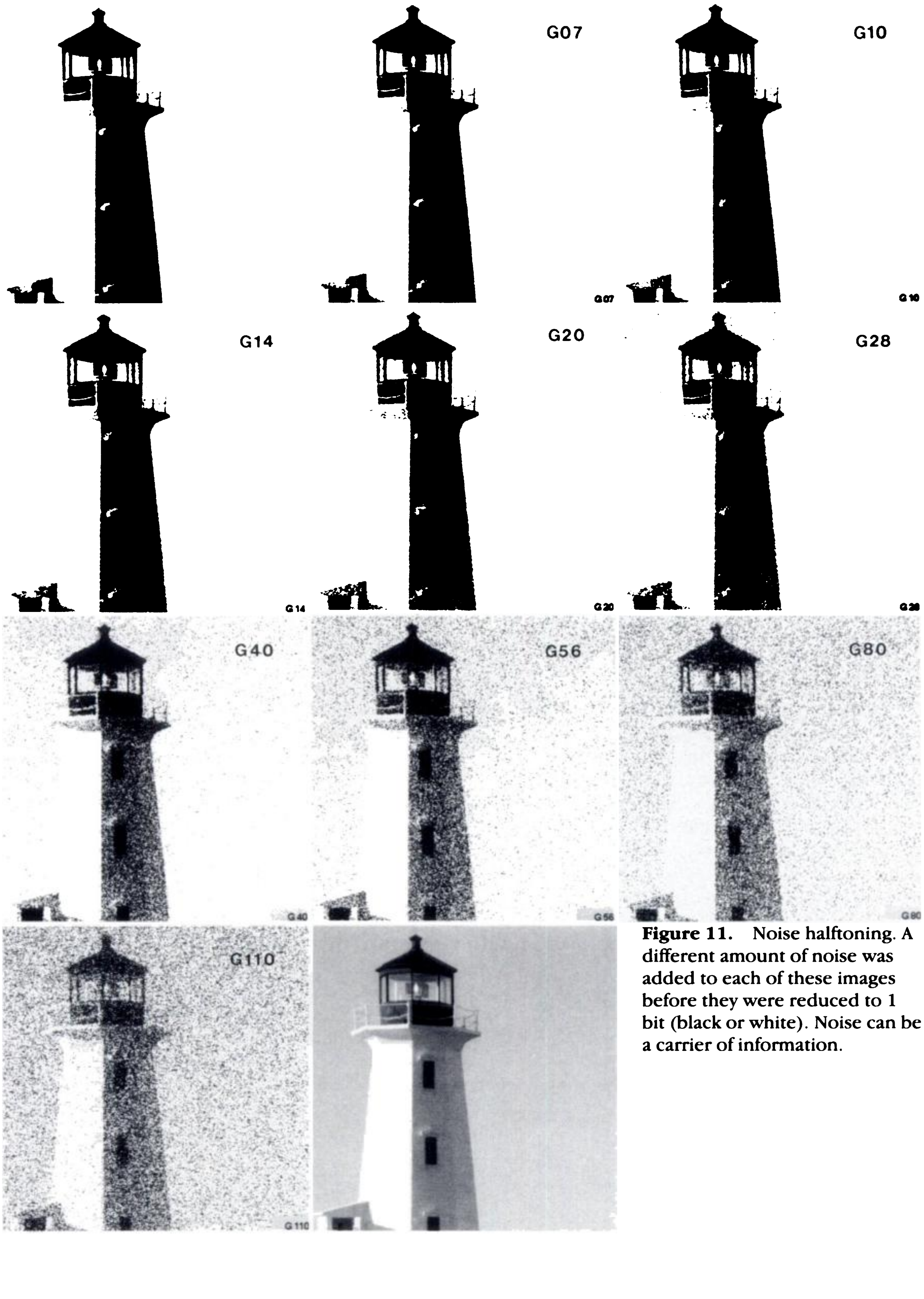

Figure 11. Noise halftoning. A different amount of noise was added to each of these images before they were reduced to 1 bit (black or white). Noise can be a carrier of information.