# *Basics for Image Quality in Digital Imaging Systems**

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## Abstract

This paper, the first in a series, examines some of the basic concepts of electronic and digital imaging, and it gives a framework for integrating various ways to assess image quality and their application to scanned and other electronic or printer imaging systems. The Image quality Circle showing how different classes of image quality are connected, flow diagrams of a full digital reprographic imaging system and the basic structure of digital images are reviewed For traceability, the figure numbers and reference numbers used in this paper are taken directly from the original CRC publication referenced above.

## Basics of Electronic Digital Imaging Systems

Following is a framework in which to sort out the many image quality engineering and technology issues that depend on these choices.

Any imaging system can be considered as composed of 10 basic parts2 illustrated in Figure 3.1 as a flow chart. To see how this applies to electronic or digital imaging Some examples may help: Probing radiation is a general term for any kind of electromagnetic radiation, the most common of which is some sort of light, and “probing” is a way of saying “falling on or passing through” an object of interest. Both digital photography and optical scanning use the same type of CCD or CMOS sensors, that is, detectors. Both create images in two- dimensional pixel format. For both, the processor may be on the sensor, in hardware resident on the system and/or also off-line in computers. Both systems can generate two-dimensional prints or displays of images using one-dimensional output applying them to one-dimensionally electronic/computer stored bit streams. Both systems use optical systems and input radiation to create the captured image including arrays of color filters to create colored images. Some input scanners use reduction optics much as a camera in macro mode but some use selfoc lens arrays which nearly contact the reflection original.

In electro-photographic printers, the detector is the photoreceptor (e.g. a Selenium plate or photoconductive belt), Processing could be electromagnetic development (There are many different kinds) and image storage may be thought of as the latent electrostatic image. In a printer, there is no actual probing radiation, Instead it is generated, often as a modulated laser beam, and the object, the computer file, is responsible for signals controlling the modulator which is part of the image forming element .

The primary difference between digital photography and input scanning is that the sensor in most photography is a fixed two-dimensional array of photosites (i.e., one-pixel sensors), while in scanning the array is synthesized by moving a long line of photosites one-pixel wide (i.e., a one-dimensional array or possibly three lines of them, one for each color) over as much of a document as is needed. This has an effect in the scanning electronics - speed of the real time circuits and opto-mechanical structures - that might create errors in positioning the line of sensors. This creates a difference from two-dimensional arrays making it appear as if the synthesized array was non-uniform. Similarly non-uniformities from one-dimensional points of light moving in two dimensions also occur in the xerographic printers which serve both input scanners and other digital imaging devices. Here the input object is a computer command file that modulates the probing radiation at a pixel by pixel location. The detector is a photoreceptor, the processing is electro-photographic transfer and development with toner and the display is the print. Storage may be considered as the latent electrostatic image on the photoreceptor.

Even an ink jet system involves scanning, however it is not a true imaging system since there is no radiation involved. But just like the electro-photographic printer, the object is the computer file but now electromechanical forces and the inkjet head become the image forming element, the transducer, depositing marks to form an image on the display(substrate). Since all of these systems involve some form of scanning, they will all be referred to in the following as “scanners” or “scanning”.

While the focus here is on imaging modules and imaging systems, scanners may, of course, be used for purposes other than imaging, such as digital data recording, from Bar Codes or to make them, for example. We believe that the imaging science principles used here are sufficiently general to enable the reader with a different application of a scanning system to infer appropriate knowledge and techniques for these other applications.

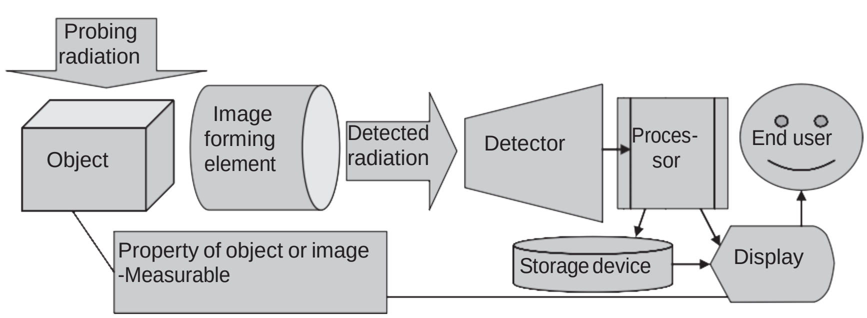



**FIGURE 3.1 The fundamental elements of any imaging system arranged in a flow diagram that approximates a typical scanner or digital camera.**

### *The Literature*

Considerable research, development, and engineering have occurred over the last decade. A few general references of note are provided as References 3–18 and elementary tutorials in References 19–23. Other more specific work of importance that may interest the reader includes: the vast technology of image processing,[17] many papers focused on specific problems in scanner image quality (see titles),[24–26] digital halftoning,[27,28] color imaging,[29–32] and various forms of image quality assessment.[33–39]

### *Types of Scanners*

All input scanners convert one- or (usually) two-dimensional image irradiance patterns into time-varying electrical signals. Image integrating and sampling systems, such as those found in many forms of electronic cameras and electronic copying devices, have sensors such as a CCD array. The signals produced by these scanners can be in one of two general forms, either (a) binary output (a string of on and off pulses), or (b) gray-scale output (a series of electrical signals whose magnitude varies continuously). An acronym sometimes used to describe units for these signals is DOL (Digital Output Level) and frequently varies from 1-256 in an 8 bit system.

The term *digital* here refers to a system in which each picture element (pixel) must occupy a discrete spatial location; an analog system is one in which a signal level varies continuously with time, without distinguishable boundaries between individual picture elements. A two-dimensional analog system is usually only analog in the more rapid direction of scanning and is discrete or “digital” in the slower direction, which is made up of individual raster lines. Television typically works in this fashion. In one form of solid-state scanner, the array of sensors is actually two-dimensional with no moving parts. Each individual detector is read out in a time sequence, progressing one raster line at a time within the two-dimensional matrix of sensors.

In other systems a solid-state device, arranged as a single row of photosites or sensors, is used to detect information one raster line at a time. In these systems either the original image is moved past the stationary sensor array, or the sensor array is scanned across the image to obtain information in the slow scan direction.

Cameras in digital photography employ totally digital solid-state two-dimensional sampling arrays. In some sense they represent commonly encountered forms of input scanners. The reader should be able to infer many things about the other forms of scanners and digital cameras from examples discussed in this chapter.

## The Context for Scanned Image Quality Evaluation

Building blocks for developing a basic understanding of image quality in scanning systems are shown in Figure 3.2. The major elements of a generalized scanning system are on the left, with the evaluation and analysis components on the right. Some readers may deal with all of these elements and it is therefore necessary to see how they all interact.

The general configuration of scanning systems often requires two separate scanning elements. One is an input scanner to capture, as an electronic digital image, an input analog optical signal from an original scene (object), shown here as a hard copy input, such as a photograph. The second scanning element is an output scanner that converts a digital signal, either from the input scanner or from computer-generated or stored image data, into analog optical signals. These signals are rendered suitable for writing or recording on some radiation-sensitive medium to create a visible image, shown here as hard copy output. The properties of this visible image are the immediate focus of image quality analysis. It may be photographic, electrophotographic, or something created by a variety of unconventional imaging processes. The output scanner and recording process may also be replaced by a direct marking device, such as a thermal, electrographic, or ink jet printer, which contains no optical scanning technology and therefore technically lies outside the scope of this article. Nonetheless, its final image is also subject to the same quality considerations that we treat here.

It is to be noted that the quality of the output image is affected by several intermediate steps of image processing. Some of these are associated with correcting for the input scanner or the input original, while others are associated with the output scanner and output writing process. These are mentioned briefly throughout ref A , with the digital halftoning process [B], cited as a major example of a correction for the output writing. Losses or improvements associated with some forms of data communication, and compression [A p214] are very important in a practical sense, especially for color. These are the subject of much work on color management.[A,p218] Additional processing to meet user preferences or to enable some particular application of the image must also be considered a part of the image quality evaluation.

The assessment of quality in the output image may take the form of evaluation by the human visual system (HVS) and the use of psychometric scaling [C] or by measurement with instruments One can also evaluate measured characteristics of the scanners and integrated systems or model them to try to predict, on average, the quality of images produced by these system elements [A,p166-201,D]. For some purposes, judging the quality of a copier for example, the detailed comparison between the input and output images is the most important way of looking at image quality, whether it be by visual or measurement means.

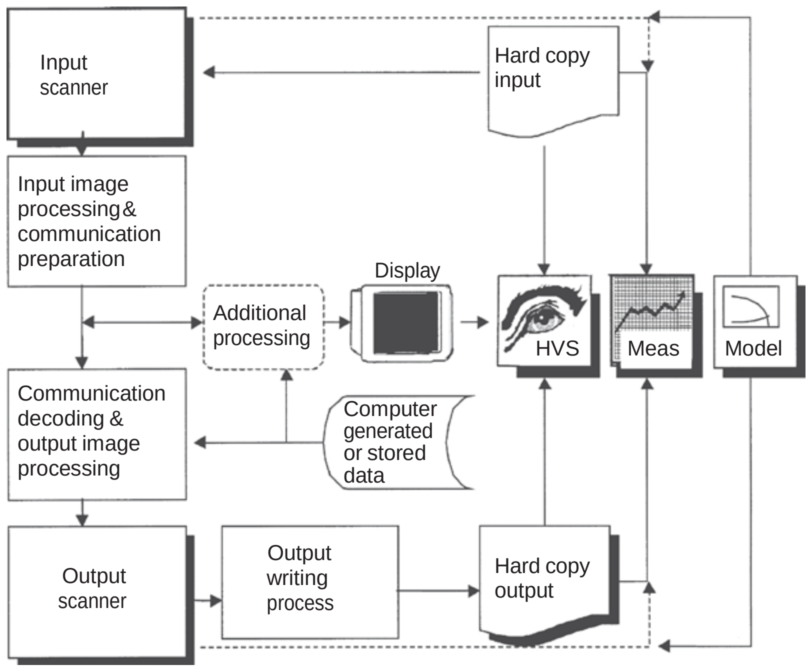



**FIGURE 3.2**
The elements of scanned imaging systems as they interact with the major methods of evaluating image quality. "HVS" refers to the human visual system. "Meas" refers to methods to measure both hard copy and electronic images and "Models" refers to predicting the imaging systems performance, not evaluating the images *per se.*

For other applications it is only the output image that counts. In some cases, the most common visual comparison is between the partially processed image, as can only be seen on the display, and either the input original or the hard copy output. In most cases, the evaluation criteria depend on the intended use of the image. A display of the scanned image in a binary (black or white) imaging mode reveals some interesting effects that carry through the system and often surprise the unsuspecting observer. These are covered in Section 3.5. Physical and visual measurements evaluate output and input images, hence the arrows in Figure 3.1 flow from hardcopy toward these evaluation blocks. Models, however, are used mostly to synthesize imaging systems and components and may be used to predict or simulate performance and output. Hence the "model" arrows flow toward the system components.

The non-scanner components for electronic image processing and the analog writing process play a major role in determining quality and hence will be unavoidably included in any realistic HVS or measurement evaluation of the quality of a scanned image or imaging system. Models of systems and components, on the other hand, often ignore the effects of these components and the reader is cautioned to be aware of this distinction when designing, analyzing, or selecting systems from the literature.

A diagram has been described by P. Engeldrum[12,40–42] called the Image Quality Circle, which ties all of these evaluations together and expands them into a logical framework to evaluate any imaging system. This is shown in Figure 3.3 as the circular path connecting the oval and box shapes, along with the three major assessment categories from Figure 3.2, namely the HVS, Measurements, and Models. In his model, the HVS category above is expanded to show a type of model he calls "visual algorithms," which predict human perceived attributes of images from physical image parameters. Examples of perceptions would include such visual subjective sensations as darkness, sharpness, or graininess (i.e., "nesses"). These are connected to physical measurements of densities, edge proiles, or halftone noise, respectively, made on the images used to evoke these subjective responses. In Engeldrum's analysis, the rest of what we call the HVS and brain combination includes "image quality models," which predict customer preferences based on relationships among the perceived attributes. This purely subjective dimension of individuals is often not included in the "brain" functions normally associated with HVS, therefore it is mentioned explicitly here. The methodologies to enable these types of analysis generally fall into the realm of psychometrics (quantifying human psychological or subjective reactions). C

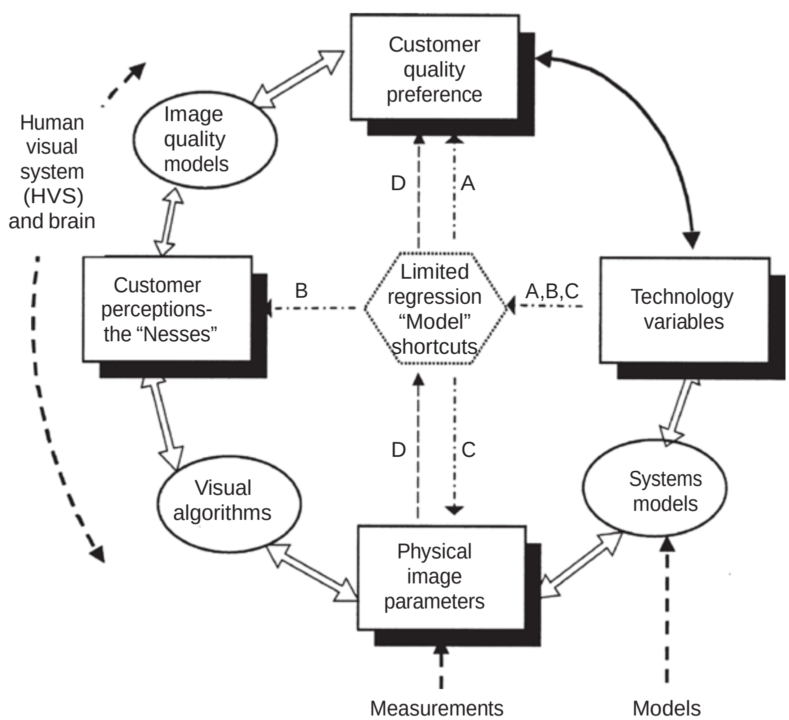



**FIGURE 3.3**
An overall framework for image quality assessment, composed of the elements connected by the outline arrows, known as the "Image Quality Circle" (adapted from Engeldrum, P.G. *Psychometric Scaling: A Toolkit for Imaging Systems Development;* Imcotek Press: Winchester, MA, 2000 and Engeldrum, P.G. *Chapter 2 Psychometric Scaling: A Toolkit for Imaging Systems Development;* IMCOTEK Press: Winchester, MA, 2000; 5–17.) and the inner "spokes" which illustrate four commonly used, but limited, regression model shortcuts as paths A, B, C, and D. The latter were not proposed by Engeldrum as part of the Image Quality Circle model, but added here to illustrate how selected examples given in Section 3.6 it the framework. The connection to HVS, measurement, and model elements of Figure 3.2 are indicated by the labels and heavy dashed lines that surround the igure.

Many authors have attempted to short-circuit this framework, following the dashed "spokes" we have added to the circle in Figure 3.3. These create regression models using psychometrics that directly connect physical parameters (path D) or technology variables with overall image quality models (path A) or preferences (path C). These have been partially successful, but, having left out some of the steps around the circle, they are very limited, often applying only to the circumstances used in their particular experiment. When these circumstances apply, however, such abbreviated methods are valuable. Following all the steps around the circle leads to a more complete understanding and more general models that can be adapted to a variety of situations where preferences and circumstances may be very different. The reader needs to be aware of this and judge the extent of any particular model's applicability to the problem at hand.

## BASIC CONCEPTS AND EFFECTS

### *Example reprographic digital imaging system*

A basic electronic imaging system may perform a series of image transformations sketched in Figure 3.4. An object such as a photograph or a page with lines and text on it is converted from its analog nature to a digital form by a *raster input scanner* (RIS). It becomes "digital" in distance where microscopic regions of the image are each captured separately as discrete pixels; that is, it is *sampled*! It is then quantized, in other words, digitized in level, and is subsequently processed with various strictly digital techniques. This digital image is transformed into information that can be displayed or transmitted, edited, or merged with other information by the *electronic and software subsystem* (ESS). Subsequently a *raster output scanner* (ROS) converts the digital image into an analog form; that is, it is *reconstructed,* typically through modulating light falling on some type of photosensitive material. The latter, working through analog chemical or physical processes, converts the analog optical image into a reflectance pattern on paper, or into some other display as the final output image.

What follows assumes optical output conversion, but direct-marking processes, involving no optics (e.g., ink jet, thermal transfer, etc.) can be treated similarly. Therefore, while one often thinks of electronic imaging or scanned imaging as a digital process, we are really concerned here with the imaging equivalent of analog to digital (A/D) and digital to analog (D/A) processes. The digital processes occur between, as image processing. In fact that is where we become familiar with the scanned imaging characteristics because that is one place where we can take a look at a representation of the image, that is, in a computer.

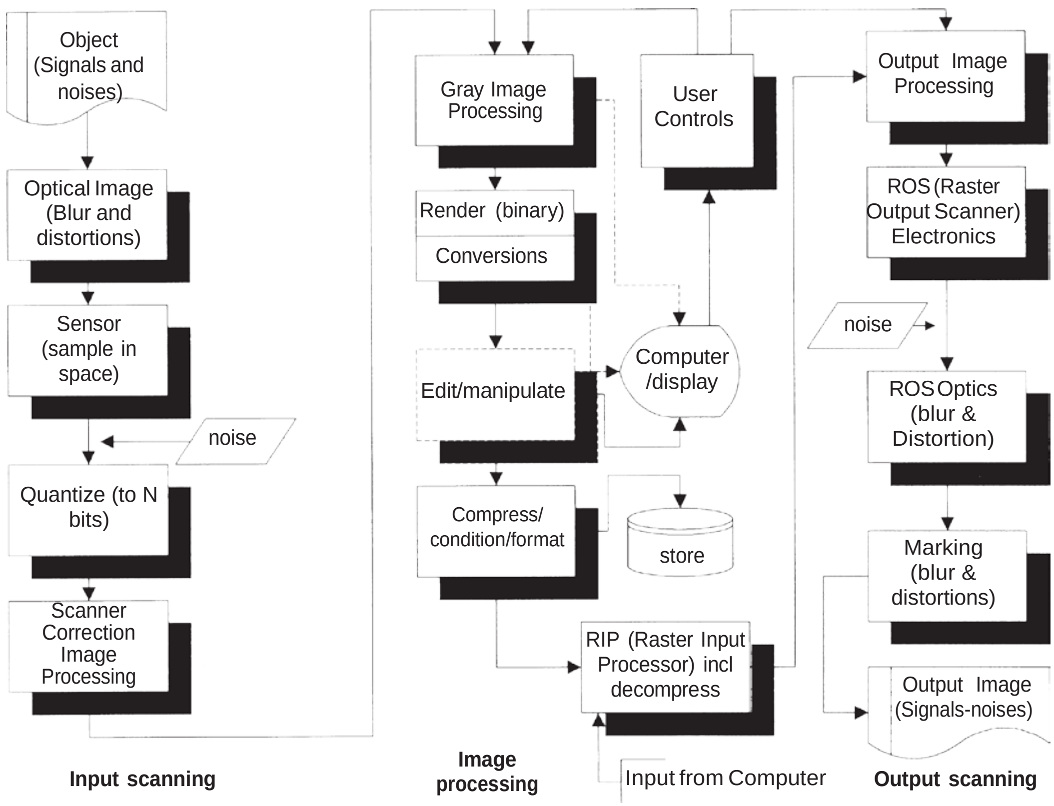



**FIGURE 3.4**
Steps in typical scanning electronic reprographic system showing basic imaging effects.

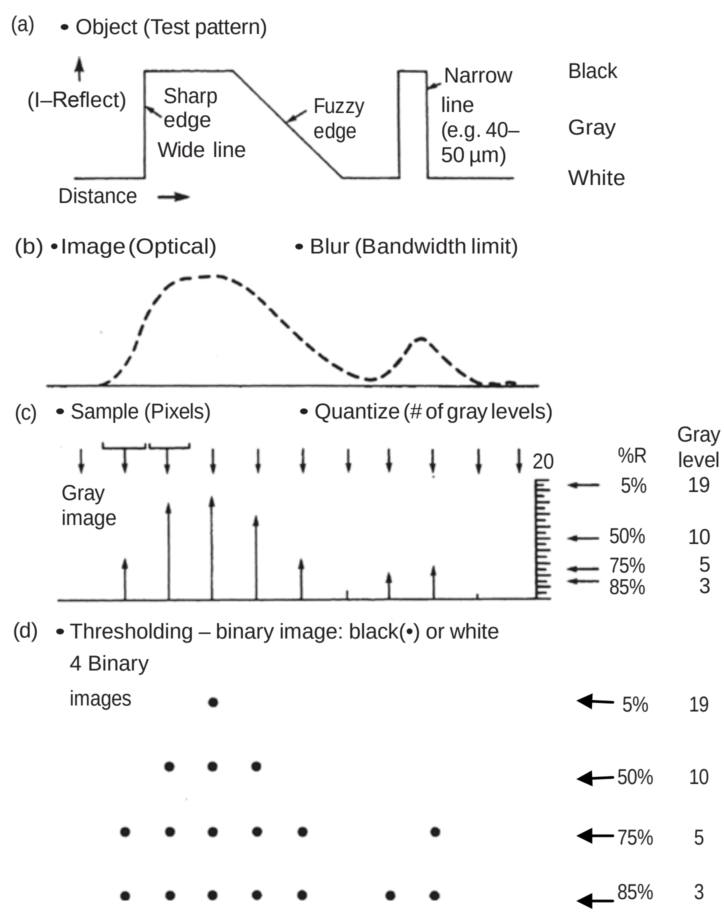
### *Structure of Digital Images*

Perhaps the most important concept for understanding digital imaging is the microscopic structure of images created by this process, paying particular attention to the A/D and sampling domain of the input scanner. While we will not focus on the original math involved, sampled electronic images were first studied in a comprehensive way by Mertz and Gray.[1]

To understand how sampling works, let us examine Figure 3.5. It illustrates four different aspects of the input scanning image transformations. Part (a) shows the microscopic reflectance proile representative of an input object: there is a sharp edge on the left, a "fuzzy" edge (ramp of greys), and a narrow line. Part (b) shows the optical image, which is a blurred version of the input object. Note that the relative heights of the two pulses are now different and the edges are sloping that were previously straight. Part (c) represents the blurred image with a series of discrete signals, each being centered at the position of the arrows. This process is referred to as *sampling.*

Each sample in part (c) has some particular height or gray value associated with it (scale at right). When these individual samples can be read as a direct voltage or current, that is they can have any level whatsoever, then the system is analog. When an element in the sensor output circuit creates a finite number of gray levels such as 10, 128, or even 1000, then the signal is said to be *quantized.* (When a finite number of levels is employed and is very large, the quantized signal resembles the analog case.) Being both sampled and quantized in a form that can be manipulated by a digital processor makes the image *digital.* Each of these individual samples of the image is a *picture element,* often referred to as a *pixel* or pel. A sampled and *multilevel* (>2 levels) quantized image is often referred to as a *grayscale image* (a term also used in a different context to describe a continuous tone analog image). When the quantization is limited to *two levels,* it is termed a *binary image.* Image processing algorithms that manipulate these different kinds of images can be "bit constrained" to the number of levels appropriate to the image bit depth (another expression for the number of levels), that is, integer arithmetic. This is effectively equivalent to many digital image processing circuits. Alternatively, algorithms may be floating point arithmetic, the results of which are quite different from the bit constrained operations.

**FIGURE 3.5**
Formation of binary images, illustrating how a single, blurred electronic image of a small continuous tone test object could yield many different binary images depending on the threshold selected.



A common and simple form of image processing is the conversion from a gray to a binary image as represented in part (d) of Figure 3.5. In this process a threshold is set at some particular gray level, and any pixel at or above that level is converted to white or black. Any pixel whose gray value is below that level is converted to the other signal, that is, black or white, respectively. Four threshold levels are shown in part (c) by arrows on the gray-level scale at the right. Results are depicted in part (d) as four rows, each being a raster from the different binary images, one for each of the four thresholds. In part (d

each black pixel is represented by a dot, and each white pixel is represented by the lack of a dot. (It is common to depict pixels as series of contiguous squares in a lattice representing the space of the image. They are better thought of as points in time and space that can have any number of dimensions, attributes, and properties.)

Each row of dot patterns shows one line of a sampled binary image. These patterns are associated with the location of the sampling arrows, shown in part (c), the shape of the blur, and the location of the features of the original document. Notice at the 85% threshold, the narrow line is now represented by two pixels (i.e., it has grown), but the wider and darker pulse has not changed in its representation. It is still five-pixels wide. Notice that the narrow pulse grew in an asymmetric fashion and that the wider pulse, which was asym- metric to begin with, grew in a symmetric fashion. These are quite characteristic of the problems encountered in digitizing an analog document into a finite number of pixels and gray levels. It can be seen that creating a thresholded binary image is a highly nonlinear process. The unique imaging characteristics resulting from thresholding are discussed in detail in a companion paper[D] and elsewhere [120]

Figure 3.6 represents the same type of process using a real image. The plot is the gray profile of the cross section of a small letter “I” for a single scan line. The width of the letter is denoted at various gray levels, indicated here by the label “threshold” to indicate where one could select the potential black to white transition level. The reader can see that the width of the binary image can vary anywhere from one to seven pixels, depending on the selection of threshold.

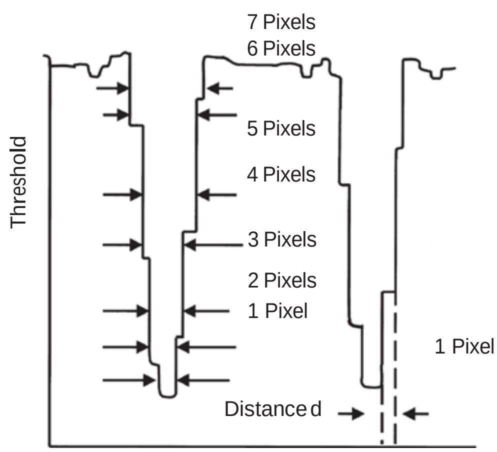



**FIGURE 3.6**
An actual scanned example of a gray scan line across the center of a letter “I.” A different representation of the effect shown in step (c) in Figure 3.5. Here the sample points are displayed as contiguous pixels. The width of one pixel is indicated. The image is from a 400 dpi scan of approximately a six-point Roman font.

Figure 3.7a returns to the same information shown in Figure 3.5, except that here we have doubled the frequency with which we sampled the original blurred optical image. There are now twice as many pixels, and their variation in height is more gradual. In this particular instance, increased resolution is responsible for the binary case detecting the narrow pulse at a lower level (closer to 0% threshold). This illustration shows the general results that one would expect from increasing the spatial density at which one samples the image; that is, one sees somewhat inner detail in both the gray and the binary images with higher sampling frequency.

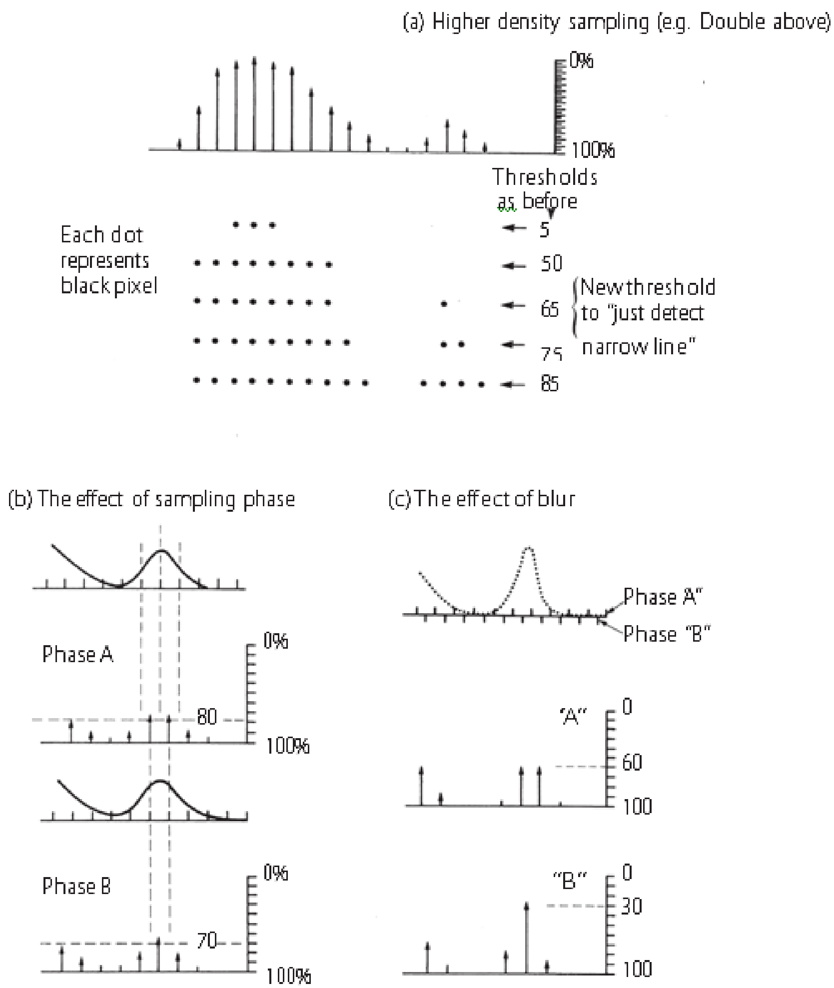
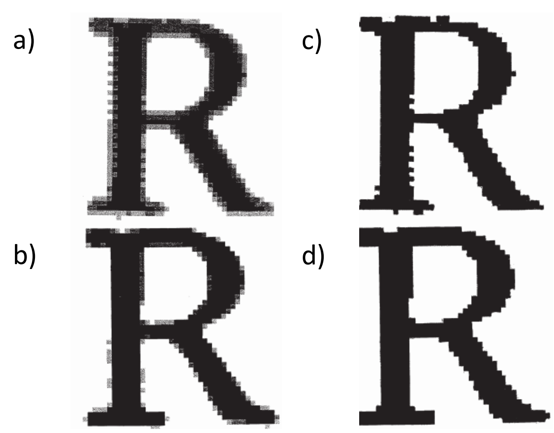



**FIGURE 3.7**
The effects of (a) doubling the resolution, (b) changing sampling phase, (c) sharpening the optical image.

This is, however, not always the case when examining every portion of the microstructure. Let us look more closely at the narrower of the two pulses [Figure 3.7b]. Here we see the sampling occurring at two locations, shifted slightly with respect to each other. These are said to be at different sampling phases. In phase A the pulse has been sampled in such a way that the separate pixels near the peak are identical to each other in their intensity, and in phase B one of the pixels is shown centered on the peak. When looking at the threshold required to detect the information in phase A and phase B, different results are obtained for a binary representation of these images. Phase B would show the detection of the pulse at a lower threshold (closer to ideal) and phase A, when it detects the pulse, would show it as wider, namely as two pixels in width.

Consider an effect of this type in the case of an input document scanner, such as that used for facsimile or electronic copying. While the sampling array in many input scanners is constant with respect to the document platen, the location of the document on the platen is random. Also the locations of the details of any particular document within the format of the sheet of paper are random. Thus the phase of sampling with respect to detail is random and the type of effects illustrated in Figure 3.7 would occur randomly over a page.

There is no possibility that a document covered with some form of uniform detail can look absolutely uniform in a sampled image. If the imaging system produces binary results, it will consistently exhibit errors on the order of one pixel and occasionally two pixels of edge position and line width. The same is true of a typically quantized gray image, except now the errors are primarily in magnitude and may, at higher sampling densities, be less objectionable. In fact, an analog gray imaging process, sampling at a suficiently high fre- quency, would render an image with no visible error (see the next subsection). Continuing with the same basic illustration, let us consider the effect of blur. In Figure 3.7c we have sketched a less blurred image in the region of the narrower pulse and now show two sampling phases A and B, as before, separated by half a pixel width. Two things should be noted. First, with higher sharpness (i.e., less blur), the threshold at which detection occurs is higher. Secondly, the effect of sampling phase is much larger with the sharper image. Highly magnified images in Figure 3.8 illustrate some of these effects. Note the grey pixels along the edges in parts a and b which illustrate a 4 grey level system, while parts c and d illustrate a binary 2 level (black and white) system.




(a)

(b)

**FIGURE 3.8**
Digital images of a 10-point letter “R” scanned at 400 dpi showing quantization and sharpening effects. Parts (a) and (c) were made with normal sharpness for typical optical systems and parts (b) and (d) show electronic enhancement of the sharpness. Parts (a) and (b) are made with 2 bits/pixel, that is, four levels including white, black and two levels of gray. Parts (c) and (d) are 1 bit/pixel images, that is, binary with only black and white where the threshold was set between the two levels of gray used in (a) and (b). Note the thickening of some strokes in the shaper image and the increased raggedness of the edges in the binary images. Some parts of the sharp binary images are also less ragged.

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B- Lehmbeck, D.R. - Basic Halftone Concepts- to be published on [www.xactiv.com](http://www.xactiv.com); technical Pubs adapted from Lehmbeck & Urbach [A]

C- Lehmbeck, D.R. - Psychometric scaling - as above [B,A]

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