

FROM PHOTONS TO BITS

A good 35-mm color negative has the equivalent of 300 million binary bits of information. If you can capture all that visual information in digital form, you can retrieve or transmit it in an instant and manipulate it at will.

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There are many ways to record optical images. One might describe Paleolithic cave paintings as the earliest imaging technology. As significant as they probably were to those who made and lived with them, these depictions were limited by the artist's skill and time, and only persons who entered the cave could benefit from them. It was not until the coming of the printing press that a particular image could be made available to a wide audience. But even then one was still dependent on the artistic skill and subjective vision of the individual artist.

With the advent of photography, almost anyone could faithfully record and convey pictorial information. Photographic images soon surpassed all previous attempts at pictorial recording in verisimilitude. By the end of the 19th century, mass manufacturing and the replacement of glass plates by film was putting photographic technology within the reach of the general public. But silver halide photography is still primarily a means of *recording* pictorial information. Photography permits only very limited interaction with an image after it's been captured.

The introduction of *analog* electronic imaging—both video and still—once again produced a great leap forward in the sheer number of images that could be captured. Video cameras in the hands of millions of people create many millions of hours of cinematic records every year. With the aid of electronic scanners and cameras, satellites can transmit images back from space without having to return any film. Even ground-based telescopes now routinely use electronic cameras, because they tolerate much longer exposure times than do photographic plates.

But as we became better and better at generating images in the 1970s and '80s, our ability to understand, manipulate, retrieve, transmit and disseminate those images was not keeping pace. That was ironic, because this same period was witnessing an astonishing revolution in the storage and manipulation of digital information. But very little of that digital manipulation had anything to do with visual images. It was almost all word processing and number crunching.

Now, however, we are on the brink of a new revolution. The advances in digital electronics, computer technology and analog-to-digital circuitry at our disposal make it possible to translate analog images into collections of digital bits. In this article I will discuss the role of

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Charge-coupled device with 1.3 million pixels. The photosensitive surface of this full-frame imager is 20.5×16.4 mm. Each pixel is a square, 16 microns on a side. (Courtesy of Eastman Kodak.) **Figure 1**

integrated circuitry, particularly charge-coupled devices, in the burgeoning technology of digital imaging. In silicon-based devices the image is captured as individual photons interact with the semiconductor material to generate electron-hole pairs. These photoproduced carriers must then be manipulated and converted to digital binary bits. This passage from photons to bits will be my principal theme.

Image capturing and processing techniques can be classified into three categories: traditional photography, analog electronic imaging and digital imaging. The table on page 45 juxtaposes corresponding elements of the processing chain for photographic and electronic imaging. But people can, and do, go back and forth between these two chains to achieve a desired end.

In photography, the print or film that stores the image in the form of color pigments can also serve as the display medium, except when the film is a negative. To produce additional copies, a film master must be made and the printing process repeated. Manipulation is done by darkroom procedures or by cutting and pasting. Because film can be made of multiple layers, with each layer sensitized to a different color, a color separation process is built into the recording material. Color-tone-scale corrections are done with a combination of filters and chemical processes. Except for the screened halftone color pictures required for printing presses (for example, the color pictures in this magazine), pigments are randomly distrib-

uted. Therefore one may regard a photographic color print or film as a superposition of analog signals distributed over two dimensions. Consequently film seldom has the aliasing problems we associate with periodic spatial sampling of a visual scene with comparable spatial periodicity. Striped clothing moving across a television screen, for example, can produce peculiar effects of a kind one doesn't see in the movies.

Film photography can produce color and monochrome images of unrivaled quality. But further manipulation of the images is a slow, manual process. That's why people have turned to electronic scanning of photographic images, or to capturing the images by electronic means in the first place.

Analog electronic imaging employs a raster scan to acquire the analog signal. An ordinary television picture is a good example: A frame is divided into line segments of amplitude-modulated electrical signals, and these discrete lines are sequentially stacked to form a two-dimensional picture. In effect one has a continuous-wave signal along a line but a discrete sampling in the direction perpendicular to the scanning line. Because the signal is electronic, one can make color corrections and image enhancements with analog electronics in one direction. Using delay lines, one can also process several adjacent lines together.

The analog signals are usually stored sequentially on some magnetic medium. Therefore one can't view the stored signals directly; they must be read back and then



a

Electronic color photograph taken with the 1.3-million-pixel CCD imager shown in figure 1 and a color-filter pattern like that in figure 4c. The halftone printing-press reproduction used here cannot really show the quality of the original photo (a). At $5\times$ magnification (b) the quality is still quite good. At $25\times$ magnification (c and d) the finite resolution of the CCD pixel array is evident. The pixelation manifest in the undoctored blowup d has been smoothed out in b and c by computer processing of the digital image data with a bidirectional interpolation algorithm. **Figure 2**



b

For two decades now CCD imagers have been getting ever better and less expensive. They have completely replaced the pickup tubes once used in consumer video cameras. The CCD has also become the device of choice for a wide variety of applications ranging from document scanners to cameras for astronomical telescopes. With advancing CCD technology and better understanding of their physics have come CCDs of high resolution, low noise and good color capability, all at a reasonable cost. Figure 1 shows a 1.3-million-pixel CCD introduced by Kodak in 1989. Figure 2a shows an example of the high-quality images one can get with a camera incorporating such a CCD.

As the demand for high-resolution imagers grows, designers of CCD photon-conversion devices face a number of challenges. Among their most urgent goals are improvements in sensitivity, dynamic range and color separation, and reduction of noise and dark current.

A charge-coupled device is an array of metal-oxide-semiconductor capacitors designed to translate an incident pattern of photons into a discrete analog signal preparatory to digitization. When the MOS capacitors are properly clocked, they move stored charges along from one capacitor to the next in a controlled manner, somewhat like a bucket brigade.³ The CCD really performs two functions: First it converts photons into electrical charge (electrons or holes), and then it temporarily stores and moves this "image-wise" charge around so it can be read in some combination of parallel and serial readout modes. At the output of the device, the signal charge is converted to voltage. Further downstream, additional electronic devices do the digitizing.

Once an image has been converted to electrons, it is transported to an output node. One advantage of CCDs is that the output node can be designed with very low capacitance. The output voltage equals the signal charge divided by the node capacitance. Therefore one can get a conversion efficiency as high as $10\text{ }\mu\text{V}$ per electron by designing the node capacitance to be as low as 10 or 20 femtofarads. Special output structures have recently been fabricated with conversion efficiencies as high as 220 microvolts per electron and rms noise levels of less than one electron per pixel.⁴

CCD imagers come in various architectures. The linear CCD scanner shown schematically in figure 3a consists of a single row of photodiodes, which capture the photons. The photodiodes are lined up adjacent to a CCD shift register, which does the readout. The picture or document to be scanned is moved, one line at a time, across

displayed, either on a video screen or as hard copy.

Digital imaging technology divides the image up into an array of discrete pixels. Within each pixel the signal is represented by digital levels for red, green and blue intensities. Unlike the raster scan of analog video, the image is represented by discrete elements in both dimensions. It is therefore susceptible to aliasing problems when the sampling frequency is lower than the spatial frequencies of details in the image. Because each pixel is represented by a number and all the pixels are accessible, the image can readily be processed, manipulated or stored by computer.

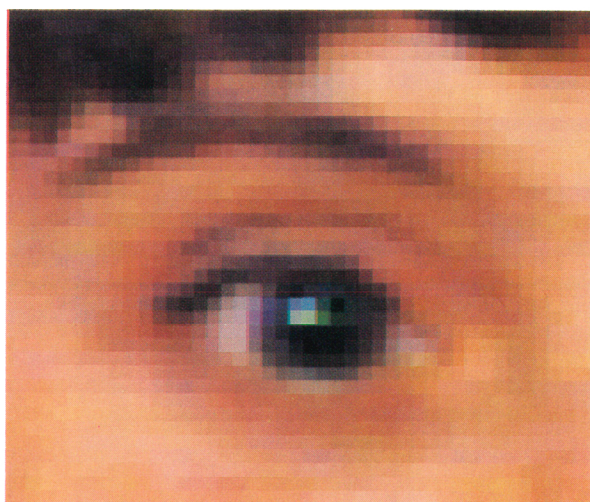
For all the convenience of digital manipulation, we do live in an analog world. The image always begins with some analog signal before its conversion to digital information. Therefore these three categories of imaging technology are closely related. One cannot say that one method is better than the others. All three may be used at different stages to get the final result just right.

Solid-state devices

Capturing the image electronically is the first step along the road from photons to bits. The first electronic devices developed for capturing images were pickup tubes,¹ introduced in the early 1930s. Solid-state imaging devices began to emerge in the 1960s. A major advance in solid-state imagers came in 1970 with the invention of the charge-coupled device.² Because CCDs use silicon technology, they can be mass-produced inexpensively like other silicon integrated circuits. CCDs are also much more compact and rugged than vacuum tube devices, and they have less noise, higher sensitivity and greater dynamic range.



c



d

the scanner by mechanical or optical means. Figures 3b and 3c show two-dimensional CCD area arrays. The device portrayed in 3b is called an interline imager, and 3c shows the architecture of a frame-transfer imager. In both of these two-dimensional configurations, only a fraction of the surface area is covered by active silicon photodetectors. But these devices have the advantage of not requiring shutters.

There are also so-called full-frame CCD imagers, like the device shown in figure 1, whose entire surfaces are covered by light-sensing pixels, but these arrays do require external shutters. Full-frame imagers are best suited for still picture applications, while interline and frame-transfer CCDs are better for imaging motion. Industry is already making interline and frame-transfer CCD imagers with as many as 2 million pixels in anticipation of high-definition television. Full-frame CCD imagers with 4 million pixels are now commercially available for electronic still photography and scientific applications.

Limitations

The image quality one can achieve with a CCD imager is subject to a number of limitations that affect both the conversion of photons to electrons and the readout of the image. Although these limitations apply also in the ultraviolet and infrared, I will discuss them mainly as they apply at visible wavelengths.

Conversion degradation. The number N of signal electrons generated at each pixel by an image optically focused on the sensor plane is proportional to the photon flux, the exposure time, the photosensitive area A of the pixel, and its quantum efficiency. As is the case with ordinary cameras, the photon flux at the sensor plane is

determined largely by the f -stop number of the optical system (that is to say, the ratio of focal length to lens aperture) and the reflectivity of the scene. The statistical shot noise of the electron signal is simply $\sqrt{N}$. Therefore sensitivity, as measured by the ratio of signal to noise, increases with pixel area like $\sqrt{A}$.

The fundamental limitation on sensitivity is thus the number of photons incident on the imaging plane. But beyond this statistical limit, the sensitivity of the detector is further diminished by other temporal and fixed-pattern noise in individual pixels. Temporal noise includes the shot noise on the dark current (that is, the signal when no light is incident) and the amplifier noise. Among the sources of fixed-pattern noise are the inevitable variations of photosensitivity and dark current from one pixel to the next.

A rule of thumb has it that one needs a signal-to-noise ratio of 40 at typical scene reflectivity to get acceptable images from an electronic still or video system. Therefore the pixel must be designed to hold at least 1600 electrons. That's the minimum signal required with shot-noise-limited performance. This number must increase as other noise sources become important. For typical photographic scenes, the shot-noise limit dictates a pixel size of at least $100 \mu\text{m}^2$.

The dynamic range of the sensor is defined as the saturation signal divided by the dark-noise level. That determines the maximum intensity ratio of scene highlights to lowlights that can be captured in an image. Nowadays electronic still and video cameras have dynamic ranges of a few thousand. Spatial resolution involves a trade-off with sensitivity. Higher resolution normally requires more and smaller pixels on a chip of given size.

Photographic vs electronic image processing

	Capture	Storage	Manipulation	Transmission	Soft display	Hard copy
Photographic	Silver halide film in a camera	Film, negatives, prints	Chemical developing and optical printing; cutting and pasting	Mail	Movies and slides	Silver halide prints
Electronic	Photosensitive solid-state devices	Magnetic, optical and solid-state media	Digital image processing	Transceivers, fax, wireless, computer networks, fiber optics	Television, projection video, LCDs	Thermal, ink-jet and electrophotographic printers

But smaller pixels, as already discussed, have poorer signal-to-noise ratios, and thus diminished sensitivity.

In going from photons to bits, the first step is to convert the incident photons into electrical charge. In most solid-state CCD devices electrons, rather than holes, are the carriers of the signal charge. In this conversion process the quantum efficiency of the detector is very important. To generate a useful signal, the incident photons must penetrate several overlayers of SiO_2 or polycrystalline silicon to reach the single-crystal silicon substrate. The thicknesses of these overlayers are on the order of a micron. SiO_2 , with a bandgap exceeding 6 eV, is transparent throughout the visible. Polycrystalline silicon, with an indirect bandgap of 1.1 eV, becomes strongly absorbing at blue wavelengths. Some of the incident photons are reflected, some are transmitted to the substrate, and some are absorbed in the polycrystalline electrode. Only those photons that are absorbed within a diffusion length of the depletion region at the upper boundary of the silicon crystal are collected and registered as signal charge. The depletion region is a few microns deep, and the effective diffusion length takes up an additional 20–100 microns. All in all, a significant fraction of the incident photons never get to make signal electrons.⁵

Rapid spatial variation in the image can also contribute to degradation of the conversion process.⁶ A pixel array has trouble handling spatial frequencies comparable with its own periodicity. High frequencies can also be washed out by diffusion of charge in the neutral substrate from one pixel to its neighbors. If the pixel is partially shielded from light by a metal shield, as is the case for an interline sensor, additional degradation results from the scattering of light to adjacent pixels by way of the layers beneath the light shield. This effect is strongly dependent on the wavelength of the incident light, because the absorption coefficient of the silicon substrate is a function of wavelength. One also gets moiré patterns and other such aliasing artifacts when the spatial frequency of the scene exceeds the sampling frequency of the pixel array.

Figure 2d is a $25\times$ magnification of a detail from figure 2a, produced without benefit of the interpolation processing algorithm used to smooth out the blowups in figures 2b and 2c. The pixelation of the unprocessed image is evident. Discrete pixel sampling, together with light scattering and electron diffusion in the substrate, generates digital images that are perforce different from the original pattern of photons incident on the focal plane.

Readout degradation. Three mechanisms that de-

grade the pixel-by-pixel charge replication of the original photon image during readout are called transfer inefficiency, smear and lag. Transfer inefficiency occurs during the transfer of charge from one phase to the next in the CCD shift register as the image information is being read out. Some of this inefficiency is attributable to defects in the CCD, but some of it is intrinsic to the process. State-of-the-art CCDs exhibit transfer inefficiency of less than 10^{-5} . That is to say, less than a part in 100 000 of the signal charge is left behind at each transfer. Keep in mind, however, that even at this very high efficiency, 8000 transfers will reduce the signal by nearly 10%.

Image lag⁷ and smear,⁸ the other two principal degradation mechanisms associated with image readout, pose problems primarily for video (as distinguished from still) cameras. But even there, the advanced design of modern imaging sensors has rendered lag and smear almost negligible.

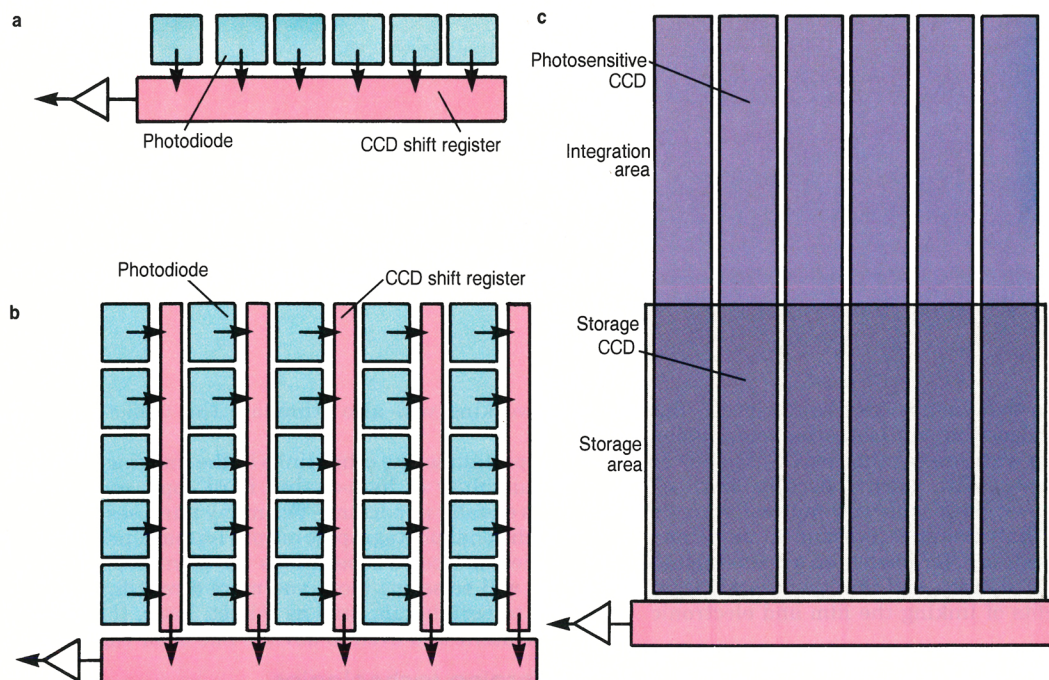
There are other degradation mechanisms that affect the pixel-by-pixel conversion of the photon image to electrical charge and its subsequent translation into digital bits. But those I've listed in this section are the principal limiting factors.

Capturing color

To capture a color image electronically, one can use either a color-sensitive beam splitter together with three separate imagers for red, green and blue, or a single imager incorporating an array of red, green and blue color filters,⁹ as illustrated in figure 4. One can take advantage of the fact that human vision is more sensitive to green than to red or blue by having more pixels under green filters. Figure 4c shows one such color-filter pattern designed to provide the best possible intensity (luminance) information in a single imaging chip without undue sacrifice of color (chrominance) information.¹⁰ Fully three-quarters of the pixels in this configuration have green filters.

Because each individual pixel sees only the color passed by its filter, one needs to reconstruct the color information from the pattern of the filter array. Once the analog signal has been converted to digital form, reconstructions, corrections and other manipulations are easily done by computer. A black reference level is stored and used for background subtraction, and the gain of each channel is adjusted to achieve the proper white balance. Defective and missing pixels are corrected for by interpolation.

Then one has to reconcile the response of the CCD to intensity and color with the rather different response of



Architecture of various CCD imagers shown schematically. **a:** A linear CCD scanner has just a single row of separate photodiode sensing elements lined up adjacent to a row of CCD shift-register elements that collect and transport the charge generated on the diodes to the readout. **b:** An interline CCD imager is basically a stack of vertical linear scanners connected by an additional, horizontal CCD shift register that collects and passes on the charge readout from the linear scanners, row by row. **c:** In a frame-transfer imager the CCD pixel is also the photosensing element; there are no separate diodes. The two-dimensional CCD array is divided for speed into two frames: The integration frame array captures an image and transfers the charge signal to the adjacent storage frame array. Thus the integration array can be capturing a new image while the storage array reads out the previous image. **Figure 3**

the display medium. CCD imagers exhibit very linear response to light intensity, whereas photographic film and prints, video and CRT displays have nonlinear response curves that approximate a power law. Therefore the linear CCD signal is mathematically corrected to match the response of the system that will finally display the image. One must also do a color-matching correction for any mismatch between the spectral responses of the imager and the display system.

To make the picture appear more pleasing, one can use smoothing functions to reduce manifestations of noise and convolution calculations to sharpen edges. All these calculational functions have been integrated onto a two-chip set.¹¹ Alternatively, they could be carried out by analog electronics. But they are much more conveniently and efficiently done by digital means, especially the more elaborate convolution calculations.

The digital integrated circuits on the two-chip set provide fast, high-quality reconstruction of full-resolution color images from red, green and blue data. They also do the color matrix matching to the display, the image sharpening and the corrections for sensor defects, as well as performing additional functions like flare correction. All these functions are performed in real time, at 30 frames a second. The chip sets use 200 000 transistors to perform 2.5 billion operations per second.

Compression and display

This impressive computational strength presents a problem when it comes to storing photographic images in

digital form, whether it be in a computer's random-access memory, on magnetic tape or disks, or in optical media.

Consider what's required for an electronic system to equal silver halide film. A 35-mm film color image contains the equivalent of 18 million pixels. Each pixel must be assigned a value on the gray scale, from dark to light. But that's only the luminance information. One must also have the color information for each pixel. Digital imaging converts the luminance and chrominance information into numbers. A modern video system with 8 binary bits per color per pixel distinguishes among 256 luminance levels and 16 million color hues for each pixel. Multiply that by 18 million pixels and you've used an enormous chunk of memory just to store one 35-mm color photograph!

The solution to managing large amounts of image data is to compress the information so that it can be stored and transmitted more efficiently.¹² There are many different algorithms for compressing image data. The objective is to achieve as much data reduction as possible without discarding so much information that the compressed image no longer accurately represents the original. There are, in essence, two broad compression strategies: In "lossless" compression, as the name implies, no data are actually lost. Decompressing gives back all the image information contained in the original data file. This means, unfortunately, that lossless algorithms provide only very limited compression ratios, typically on the order of 3:1. By contrast, "lossy" compression can achieve much higher compression rates, but at the cost of

discarding some data that cannot later be retrieved. But with the right lossy algorithm one can, after compression and retrieval, end up with images that look to the eye as good as the original. With such "visually lossless" techniques one can nowadays achieve compression ratios of 20:1 or better. That makes it possible to store and rapidly access hundreds of color images on a conventional magnetic tape or optical disk. And that's where we begin to see the real benefits of linking the film and electronic imaging chains.

Once the image is digitized it can be manipulated at will. A wide variety of image manipulation software systems are already commercially available, ranging from basic packages that run on personal computers to very powerful graphic arts systems. Working in the digital domain lets users recolor, resize, reposition and superpose images. Computer-generated images can be combined with real film images. Special cinematic effects that now take weeks to create will soon be produced in a day.

The digital domain gives us the ability to transmit and display high-resolution images. The growth of these technologies is greatly facilitated by the burgeoning of worldwide telecommunications and by the proliferation of fiber optics. The inexorable spreading of the fiber optic network has been aptly called the second wiring of the world. This digital highway will carry immense amounts of information worldwide. It is especially important for cost-effective transmission of image information. The growing use of fiber optics in telecommunications and cable systems makes almost unlimited bandwidth available for image transmission. The proliferation of comput-

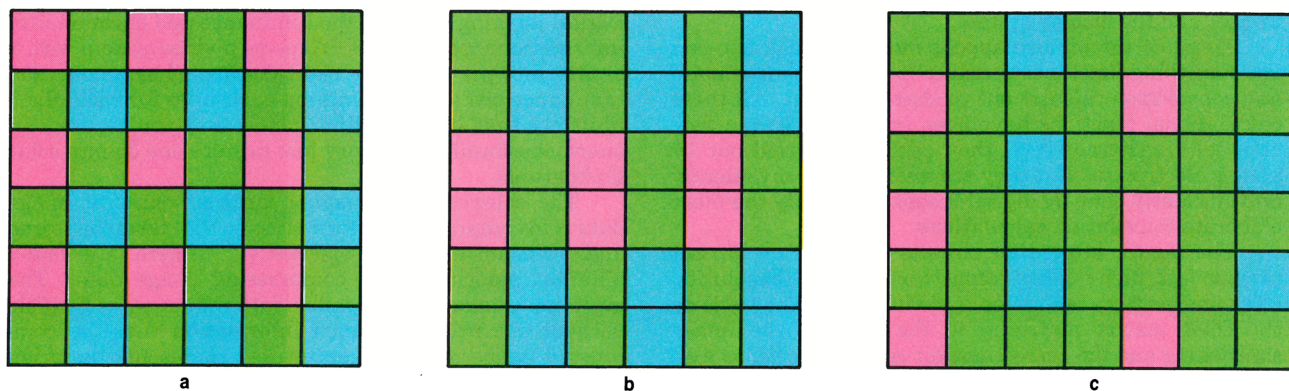
er networking will also stimulate the traffic in digital images.

Important as the other links in the imaging chain are, the availability of high-quality hard copy, especially in color, is equally important. For many purposes one wants the traditional photographic output formats: prints, transparencies and color separations for print reproductions. But we will be seeing more and more direct digital image output to peripherals such as ink-jet, laser, thermal and LED printers, and even to devices like color copiers.

Converging technologies

We are witnessing a convergence of technological trends that should greatly enhance the use of digital images: The cost of digital memory has dropped from \$400 to \$40 per megabyte in just the last five years. In that same period the advent of fiber optic networks has increased the data transmission bandwidth by a factor of 10 000. On top of this, computer processing speed has risen from 1 million instructions per second to over 100 mips. Equally important is the fact that the cost of putting all that computing power to work has been falling by orders of magnitude. We can now implement image-processing algorithms requiring 10 000 mips for just a few hundred dollars.

Solid-state imaging based on charge-coupled devices has made significant progress in terms of both pixel density and imager performance. Area image sensors with 4 million pixels on a single chip are now commercially available,¹³ and 16-megapixel CCDs have been demonstrated.¹⁴ Linear color sensors as long as 8000 pixels are in



Patterns of color-filter arrays used to capture color images with CCD arrays. Each filter covers one CCD pixel. Green filters predominate because the eye is more sensitive to green. Early filter patterns (a) were 50% green. This arrangement requires delay-line interpolation because not every row has both red and blue filters. In the standard television camera pattern (b) every horizontal line is duplicated by a neighbor. A pattern that maximizes intensity information by employing 75% green pixels (c) nonetheless yields satisfactory color information. **Figure 4**



Color image captured with a 1.6-million-pixel CCD array covered by the filter pattern shown in figure 4a. **Figure 5**

use today for scanning film and documents.¹⁵

Advances in large-scale integrated circuitry have given us very fast 12-bit analog-to-digital converters, image manipulation circuits and compression-algorithm hardware that let us implement digital imaging technology in a wide variety of applications. Astronomers¹⁶ and atomic spectroscopists¹⁷ have come to rely increasingly on CCDs. High-speed photography with electronic sensors has achieved rates of 2000 full frames per second and 12 000 partial frames per second.¹⁸ Video cameras have become commonplace, and electronic still cameras¹⁹ are finding wide use in commerce, industry and journalism.

Figure 5 shows an example of the quality of the color pictures one gets with electronic still cameras. But graphic artists are going beyond the quality of the unadulterated picture; they are scanning prints or negatives with high-resolution linear color CCDs and storing the data in workstation computers so that the images can be radically manipulated for any special purpose.¹⁵ The result of the graphic artist's ministrations can then be printed by traditional photographic means or by a digital printer. Motion picture film can be scanned at very high data rates with specially designed linear sensors, and the resulting digital images can be displayed by high-definition television.²⁰

The information content of pictorial images is generally far greater than that of the data files traditionally encountered by computers. Thus we cannot have a massive migration of images into computers without the development of image conversion devices capable of processing and transferring data at very high rates. Sixteen-bit accuracy will probably be needed for many applications. There is an urgent need for devices that can transfer images rapidly and efficiently between analog and digital forms. We will have to process and move images at gigahertz rates. The goal is to develop systems that will handle images as rapidly and efficiently as we now handle text and numbers.

As we approach the millennium, many new applications doubtless await us. The consummation of the union between photography, electronic image capture and high-speed computing will bring forth a prodigious increase in our ability to capture, store, manipulate, transmit and display images in vast numbers. If it is true that a picture

is worth a thousand words, then the language of the future may very well be digital imaging.

I would like to thank Bruce Burkey and Tom Lee for their help in writing and editing this article. I would also like to thank Barbara Carpenter for typing the manuscript and drawing several of the original figures.

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