Billions of Bits/Minute*

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(Abstract is on next page)

INTRODUCTION

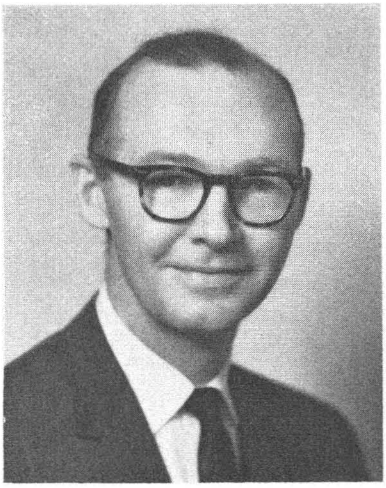
PRACTICALLY all of the information problems encountered in aerial photography, whether for reconnaissance or map making, have their counterpart in other types of communication systems. This paper will emphasize the intuitive sameness between problems as well as their solutions, despite differences in concept, language and hardware. The common purpose of photography, radio, television, etc. is to transfer information from one point to another. Two important features of information transfer are (a) the rate at which information is transferred and (b) the fidelity with which it is transferred.

The 'bit" is a convenient measure of information *amount* and *rate*—useful for comparison of different communication systems. The "fidelity" with which information is transferred involves other factors, not conveniently expressed in terms of the bit. Consequently, this paper exhibits two modes of thought, one dealing with information in digital form (*bit notation*) and the other in analog form (*graphic notation*).

THE BIT

Modern electronic computers consist of a vast number of on-off switches capable of counting to extremely high numbers, with extremely high accuracy, at an extremely high rate. Nevertheless, the fundamental building block is a simple device which gives a simple "yes" or "no" answer to a direct question. Complicated questions merely require more identical devices. In communication theory, the elemental unit of information is the "bit." Complex information, answers—not questions, is a combination of elemental answers—each of which indicates one of two possible choices. The choice may be between "yes" or "no," "dot" or "dash," "on" or "off," "is" or "ain't," "black" or "white," etc.

In the game "Twenty Questions," the moderator can only answer yes or no. Yet, with twenty well-placed questions, the panel usually isolates the given subject—a very specific answer. Twenty on-off switches, in combination, can represent a million different answers (2 raised to the 20th power) where the specific answer (number) is represented by a combination of ones and zeros, twenty digits long. The "bit" is the basis for a simple numbering system where each digit is represented by only one of two possible symbols (See Figure 1).



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For this paper, digital information will be expressed as a number in binary notation. In other words, the signal will be reduced to the presence or absence of a signal representing either yes or no. In all of the communication systems considered here, the signal may have many shades of "maybe" between yes and no. However, the same simplifying assumption is made for all, with no detriment to the comparison of transfer rates.

INFORMATION TRANSFER

The ways in which bits of information are transmitted from source to detector demonstrate both the similarities, and differences, between a variety of techniques which link man with man. Most systems use a sequential method of transfer. This involves a point-

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source and a point-detector, between which information flows bit after bit after bit. Smoke signals used one source, from which the presence or absence of smoke was a bit of information. Telegraph and telephone use a single wire between transmitter and receiver. Radio operates between the transmitting aerial and a receiving aerial. Television uses antennae. Each of these systems has two points in space, between which information flows in time sequence.

Photography, on the other hand, transmits information, at the same time, from a multiplicity of points in the source to corresponding points in the detector. Billions of luminous points (the subject being photographed) are simultaneously connected to the recording emulsion (billions of photosensitive points ready to respond to light). (See Figure 2).

SEQUENTIAL TRANSFER RATES

The telegraph operator works his key about 5 times per second. Each time, he indicates whether the corresponding bit of information is a dot or a dash. If the answers are flowing at a rate of 5 cycles/second (each cycle being the time during which a question may be asked), then the information rate for telegraphy is 5 bits/second.

The telephone has a bandwidth of approximately 2,000 cycles/second. The lowest frequency is zero cycles/second (silence) and the highest frequency transmitted is 2,000 cycles/second. Although used for complex waveforms, it can be used for digital signaling (as in the telegraph) and has an information rate of 2,000 bits/second.

Radio has a higher information rate, allowed by FCC regulations to transmit a bandwidth of 15,000 cycles/second. This is superimposed on a much higher carrier frequency but, just in terms of the audible information, extends from zero cycles/second (silence) up to a maximum frequency of 15 kilocycles/second. Again, the usually complex wave form could be replaced by a binary system with an information rate of 15,000 bits/second.

Television bandwidth is greater than radio, with a video signal of 4 million cycles/second. Although the signal is transmitted sequentially, the distribution in time is converted into a distribution in space at the receiver. Consequently, the signal can be used to pro-

ABSTRACT: *Information is considered in both digital and analog form in comparing telegraph, telephone, radio and television with photography and photographic printing. A digital transfer rate of billions-of-bits-per minute is possible only with photography since information is transmitted* simultaneously *rather than* sequentially *as required in the other forms of communication. The similarities among systems are more striking than their differences. The fidelity of photographic reproduction depends on both frequency response and/or noise of the particular chain. The spread function (of light) for each link in the chain determines over-all response, and is a function of lens distortions, diffraction at boundaries, scattering of light in emulsions, and the geometry of light source versus contact in contact printing. Shape of the sine-wave response curve (contrast versus space-frequency) indicates whether the chain exhibits high acutance or high resolution. Its shape can be modified by automatic dodging during printing—the equivalent of automatic volume control in radio. The photographic emulsion, being an amplifier, also influences the shape and bandwidth of the frequency response curve. Like other amplifiers, it has limited dynamic range and variable gain (gamma) which, in combination, determine the largest amplitude (contrast) which can be amplified. Also, it possesses inherent noise (grain) which determines the highest frequency (smallest size) signal which can be detected at the output.*

Recognition of these similarities, and their role in photographic reproduction, has prompted redesign of the LogEtronic continuous contact printer, Model SP10/70A, which now prints at a rate of 20 feet per minute, at 160 lines per millimeter resolution, with automatic dodging and automatic exposure control on 9″ wide materials—an information transfer rate of approximately 30 billion bits-per-minute.

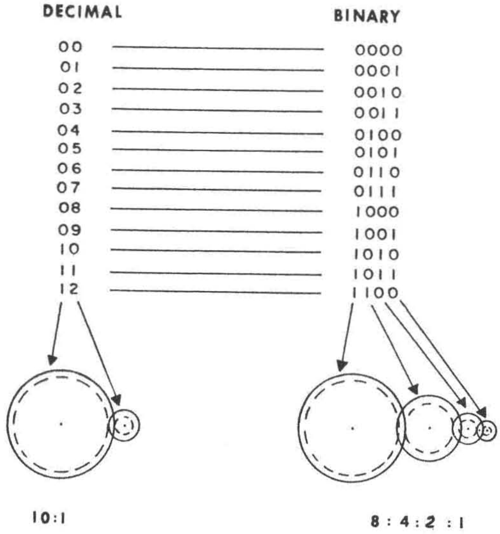

FIG. 1. Counting in the decimal system progresses through each of the available symbols and then proceeds to the next digit. The mechanical analog is the odometer—a chain of gears, each with ten times as many teeth as the preceding gear. Hence, it takes ten revolutions of the fastest gear (least significant figure) for one revolution of the next fastest, etc. The mechanical analog in a binary system is a chain of gears, each with twice as many teeth as the preceding gear. The fastest gear makes two revolutions per revolution of the next fastest gear, etc.

duce a dot pattern on the face of the receiving tube. As before, the information rate is equal to the bandwidth—4 million bits/second. Since a new picture is formed every 1/30 of a second, a binary signal occurring at 4 million cycles/second would produce a pattern having approximately 130,000 dots—regardless of the size of the tube.

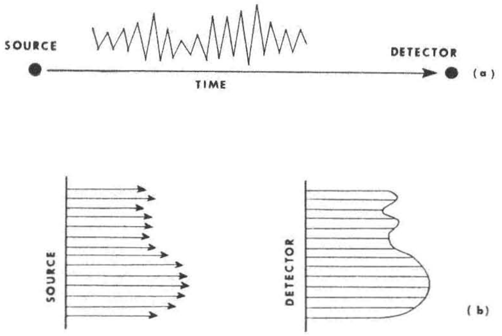

FIG. 2. In electronic communications, information arrives at a point in space—distributed in time (Fig. 2a) whereas in photography, information arrives at a point in time—distributed in space (Fig. 2b). However, the information rate (measured in bits per unit time) can be calculated for both kinds of systems.

For sequential transfer the information rate may be as low as one bit every 10 seconds (smoke signals) up to 4 million bits in each second (television).

PARALLEL TRANSFER RATES

The digital information rate, for photography, can be calculated, and expressed in bits per second—for direct comparison. (See Table 1).

Assume that the subject to be photographed consists of an infinite number of points each of which either emits or does not emit light. It is known that the camera cannot record an infinite number of adjacent points alternating between black and white (limited resolution), and that a certain period of integration (exposure time) is required by the emulsion to record an image. The information rate of a typical camera can be calculated by assuming a lens/film combination resolving 50 lines/millimeter on a 9″×9″ format during an exposure of 1/50 of a second. A camera able to resolve 50 lines/millimeter can reproduce 2,500 square dots (bits) per square millimeter. Exposing a 9″×9″ area in 1/50 of a second represents an information transfer rate of about 6,000 million bits/second. This is more than 1,000 times as fast as television. But—remember that television operates continuously, presenting a new picture every 1/30 of a second, whereas the camera operates intermittently—requiring about one second for transport of a new piece of film into the exposing position. Since the camera is exposing only 1/50 of a second out of each second, the continuous information rate is reduced to about 100 million bits/second—still 25 times as fast as television.

TABLE 1

COMPARATIVE TRANSFER RATES

System	*Bits/Second*
Smoke	0.1
Telegraph	5
Telephone	2,000
Radio	15,000
Television	4,000,000
Intermit. Camera	100,000,000
Strip Camera	3,000,000
Strip-Printer	500,000,000

If, instead of an intermittent camera, there is considered a strip camera, a continuous rate of approximately 3 million bits/second is calculated. This assumes an airplane at 25,000 ft., flying at 300 knots, and a camera with a 12″ lens resolving 50-lines-per-millimeter. Here, the information rate is limited by the speed of the aircraft (not the camera) since the film needs to travel at only 1 foot-per-minute.

With a continuous contact printer, such as the LogEtronic SP10/70, exposing 9″ material at a rate of 20 feet/minute and resolving 160 lines/millimeter in the print, there is calculated a rate of 500 million bits/second which is about 100 times as fast as television (or strip photography), and about 5 times as fast as intermittent photography—on a continuous basis.

None of the rates calculated above represent the limit of what can be done with any of the systems, but only represent typical practice—limited by either government regulations, trade standards, economy, tradition or present state of the art. Some technical limitations are discussed in the following, with particular emphasis on the sameness between concepts—with the confidence that recognition of the sameness between problems will lead to analogous solutions.

BANDWIDTH AND SHARPNESS

One test of a hi-fi amplifier is its ability to reproduce, at its output, a square-wave signal applied to its input. As the frequency of the square-wave is increased, the output signal (as seen on an oscilloscope) begins to show rounded corners, later on becoming a sine-wave of reduced amplitude and eventually becoming no signal at all. The same kind of tests are performed with lenses, using resolution targets for the input and a microscope to monitor the output. Measures of image-sharpness such as "acutance," "spread function," "sine-wave response" have become popular but, although related in fact, are seldom related in literature. An attempt will be made here to relate them and to persuade the reader that the same concepts apply to information transfer in any communications system.

The sole purpose of a lens is to transmit each bit of information from the object to the image, without distortion. The object consists of billions of bits, from which just one will be selected. This particular bit is a mathematical point source of light. The lens, ideally, would collect a multitude of light rays from said point and direct *all* of them to a point in the image plane (Figure 3). A plot of brightness versus distance would yield a straight vertical line (Figure 3b) showing all of the light concentrated in said point, with none escaping to other regions of the image plane. However, lens aberrations will spread light outside the intended point—giving the distribution shown in *3c* or *3d*. The total amount of light is the same for *b*, *c*, and *d* but its distribution in space is different, one having sharp points with broad skirts, and the other—flat tops with steep sides. A formula, describing either of these shapes, would be called the spread function.

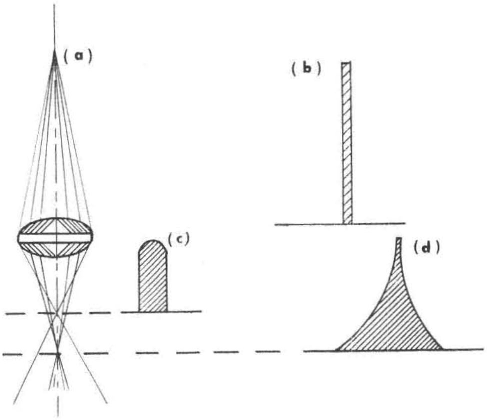

FIG. 3. Ideal (b) versus real (c) and (d) point spread functions of object (a).

The pointed distribution (Figure 4—upper) will be capable of high resolution, meaning that as the shapes get closer together and begin to merge, some brightness variation (due to the sharp peaks) will be retained, allowing a person looking through a microscope to observe lines which are separated from each other. However, the square shape (Figure 4—lower) will produce an image with sharp edges, described as "crisp" or "snappy" meaning that all boundaries will exhibit a steep gradient—high acutance. However, it is obvious that as these shapes become closer together, they will merge into a continuum much sooner than the one with the sharp peaks.

In both cases, as shapes begin to merge, the resulting plot will show a small amplitude ripple superimposed on top of a continuous or steady state condition. In electronics, this would be a small *AC* component superimposed on a large *DC* component. The middle pair (upper and lower) show the microdensitometer trace which might result from a film developed to "normal" gamma. However, the same image falling on a film, and developed to a higher gamma, might produce the right hand pair of plots. Note that development to a higher gamma not only in-

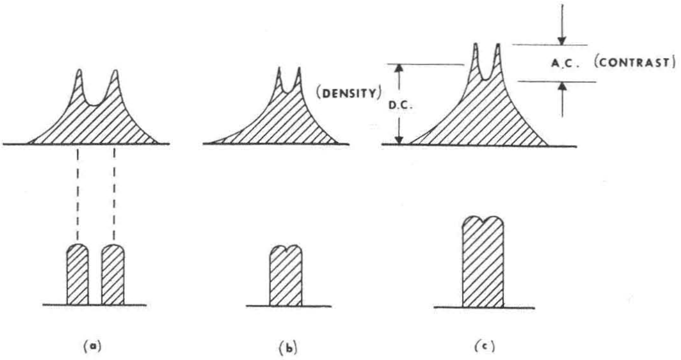

FIG. 4. Adjacent spread functions—high resolution (upper), high acutance (lower), reduced spacing, (a) to (b) and increased gamma (b) to (c).

creases the *AC* component (wanted information) but also increases the *DC* component (non-informative). The developer is a *DC* amplifier with high-frequency response (broadband).

Figure 5 shows the kind of a plot derived from sine-wave response measurements. Actually, it is a plot of just the *AC* component of the spread function plots shown in Figure 4 versus the distance between points in the image. As can be seen, the contrast at low frequencies (large spacing) permits the points to be reproduced at maximum contrast (*AC* amplitude). However, as the points get closer together at increasing frequencies, they begin to merge with each other, and the *AC* component (microcontrast) eventually falls to zero—no signal at all. This plot disregards the *DC* component (average density) since it is non-informative.

The curve of the spread function with flat top and steep sides holds up well with increasing frequency, but suddenly drops as the steep sides begin to merge. However, the curve of the spread function with the sharp peaks begins to lose amplitude early, as the skirts begin to merge, but manages to retain a small *AC* component at much higher frequencies. The flat top—steep side spread function produces a frequency response curve which describes a high acutance system. The sharp peak—broad skirt spread function produces a frequency response curve corresponding to a high-resolution system. The ideal system, not shown, would be a horizontal straight line going out to infinite frequency, representing both high-acutance and high-resolution with the ideal spread function shown in Figure 3b. However, life is not like that. The same factors apply in contact printing where, ideally, a point in the negative would be reproduced as a point in the print.

In Figure 6a light emanates from all points on the surface of the light bulb, subtending some small angle, measured from a point in the negative to the extreme edges of the light bulb. The same is true with a broad source as shown in 6b except that the subtended

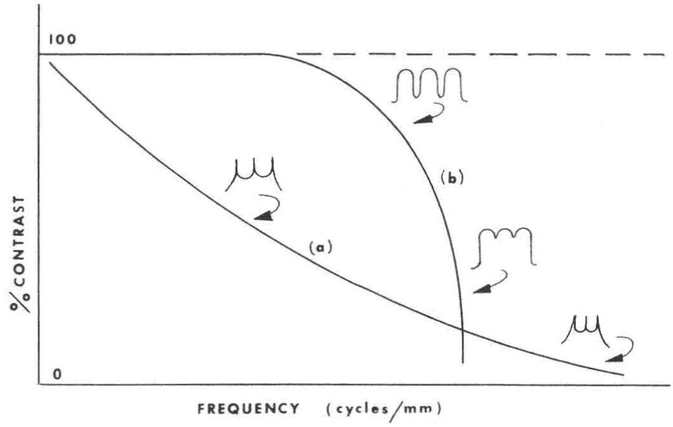

FIG. 5. Sine wave response curves—high resolution (a) high acutance (b).

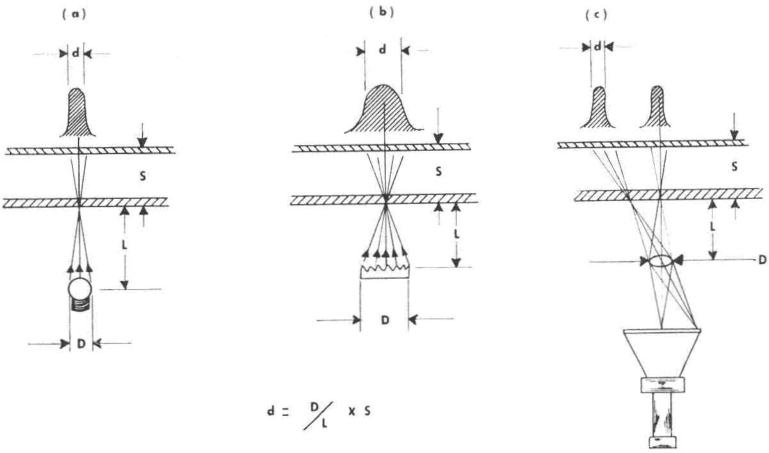

FIG. 6. Negative and print material (slightly separated) illuminated by a small light source (a), a broad diffuse light source (b), and a cathode ray tube light source, projected by lens (c).

angle is much larger and diameter of the spread function (d) is much broader. The same also applies to 6c, but here the angle is not determined by the size of the light source itself, but by the size of the lens used. It is not influenced by the sharpness of the projected image, or by size of the spot on the face of the cathode ray tube. In contact printers, the spread function is determined primarily by the ratio of the projection distance (*L*) to the lens (source) diameter (*D*). The larger this ratio, the closer the spread function approaches ideal. Ultimate arrival is prevented by diffraction in the space between emulsions.

Even with perfect geometry, residual spread of light will persist—because of diffusion within both layers of emulsion (negative and print).

It has been made evident, that the frequency-response of an optical system, whether connected by projection or by contact, is determined by the particular spread function and may reproduce with either high-acutance or high-resolution. In the same way, an electronic amplifier may have a frequency-response which is broad band with sharp cut off (high acutance), or with extended high-frequency response (high-resolution). Therefore it seems that bandwidth and image-sharpness are related in a fundamental way.

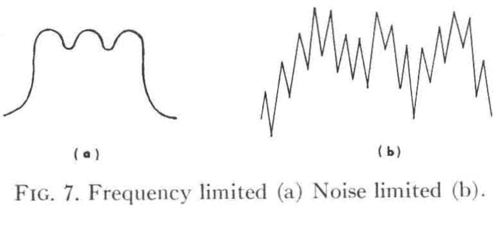

FIG. 7. Frequency limited (a) Noise limited (b).

NOISE AND GRANULARITY

So far there has been considered only the limitations of spread function on the fidelity with which information can be transmitted from source to detector. In electronic communication, a factor of much concern is the signal/noise ratio where noise may be due to random fluctuations in the atmosphere, thermionic emission, interception of unwanted signals, etc. The equivalent effect in photography is produced by granularity in the emulsion. Figure 7 shows two different ways in which sharpness may be limited. Neither case reproduces the three well defined bars in the input target. Instead, definition is lost in 7a due to merging of bars. Definition in 7b is lost due to the extremely high noise component superimposed on the signal. In testing photographic systems, there arises the question whether the spread of light is the limiting factor or whether granularity of the emulsion is limiting. In general, when light spread is at fault, the loss of definition occurs as in Figure 7a whereas grain produces loss of definition as in 7b. The distinguishing clue is whether the image merges or whether it breaks apart. (See Figures 8a and 8b.)

Noise in an audio system sounds like hissing. In television, it is readily seen in signals from a distant station. If possible to see a single television frame, the noise from even a local station would be intolerable. However, the noise is random, and when viewing several frames in rapid succession, the eye integrates

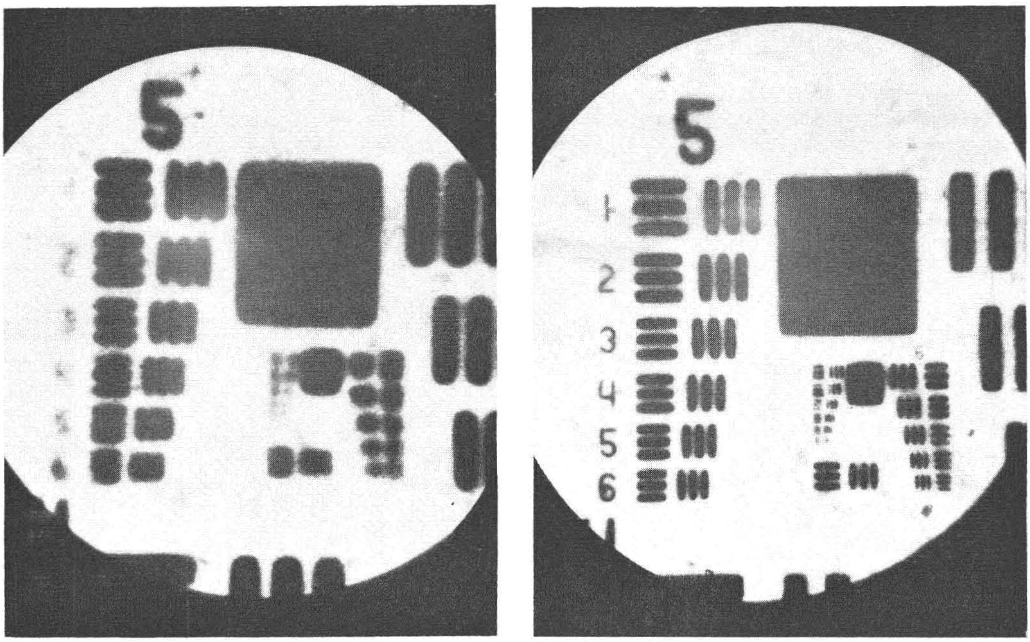

FIG. 8. Enlarged section of a high contrast resolution target printed on the LogEtronic SP10/70 two different ways. The target of Figure 8a (left) was printed through the film base with the emulsions out of contact by the thickness of the film. Here, the resolution is limited to 32 lines per millimeter by the spread function. Figure 8b (right) on the other hand, was printed with the emulsions in contact, as is normally done, showing a resolution of 180 lines per millimeter, at which point the bars are breaking up into the granular (digital) structure characteristic of the emulsion—not limited by the printer but by the film itself.

out the effect of the random noise—permitting the picture (mostly repetitive) to come through well defined against a noisy background. The same kind of effects are observed in small motion picture films. An individual frame, when viewed at high-magnification shows a very grainy structure. However, this grain (random noise) is integrated out during projection, and is not nearly so disconcerting as the grain in a greatly enlarged print from a single frame of the same film.

Noise, in photography, is due to random clumping of the individual silver grains which make up the image. Each grain is opaque to light and is equivalent to the elementary on-off switch previously described in the computer. Tones between black and white are made up of clumps of varying sizes and spacing. A given optical density, composed of a few very large clumps, appears grainy upon close inspection. However, if the same density is made up of many more smaller clumps (packed closer together) the resulting image is termed "fine-grain" and exhibits a much higher signal/noise ratio—being higher in frequency with smaller apparent amplitude.

In communications, the signal/noise ratio is generally expressed for a given bandwidth of frequencies. Likewise, in photography the signal/noise ratio must be expressed in terms of space-frequency or in other words, the relationship between size of image (signal-frequency) and size of the granular clumps (noise-frequency) in the emulsion. Definition limitations due to the spread function (property of the lens) are more apt to occur in large lenses whereas limitations due to noise (property of the emulsion) are more likely with small formats.

GAIN AND GAMMA

In every communication system, there is a transducer which converts the information into a form which can be perceived—audible or visible. The earpiece of the telephone, the loudspeaker of the radio, the cathode ray tube of television, the developer in photography—all represent the point at which this transformation takes place. In each case, there is a signal level below which the signal cannot be perceived, even though the transformation has successsfully occurred. For audible signals the threshold signal is 1 decibel. For visible signals the contrast threshold is about 0.04 log. units. In television, these would be units of log. relative luminance, whereas in photography, they would be units of relative density.

In either case, the contrast perception

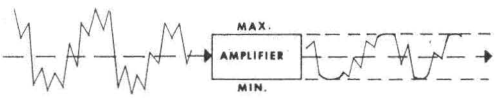

FIG. 9. Output signal limited by dynamic range of amplifier.

threshold of the eye is a complicated function of average brightness reaching the eye, proximity of the two points in question, as well as their relative brightness. Obviously, two gray cards which differ in density by only 0.04 units (held three feet apart at arm length) will appear to have the same density. However, when brought together the density difference becomes apparent. Also, when peering into a region which has a density of approximately 2.0, surrounded by large areas of density zero, and expecting to perceive a small density difference—one is either optimistic or has never tried it. Blocking out the surrounding bright area is a big help.

Recognizing that physiological thresholds actually exist makes obvious that mere transformation (to either audible or visible signal) is not sufficient for perception by the eye or the ear. There must also be amplification. In radio, this is the volume-control. In television, it is the contrast-control. In photography, it is development of the latent image. These controls do not determine the frequency-response of the system, or its signal/noise ratio, but only the size of the signal (its amplitude). As one turns up the volume or contrast (gain), or turns up the developing time (gamma), almost everything about the signal is increased. Increased is the amplitude of the signal, the amplitude of the noise, the amplitude of the low-frequencies and the amplitude of the high-frequencies. The signal is brought above our perception threshold.

All amplifiers have a limited dynamic range beyond which the output signal cannot be driven. Prior to reaching this saturation limit, the signal becomes distorted and the relative amplitudes coming out are no longer faithful reproductions of the relative amplitudes going in. In a sound system, with the volume turned up to hear the soft passages, the loud passages can become an indistinguishable clutter. On the other hand, with the volume turned down for clean fortissimos, small signals such as needle scratches may disappear below the audible threshold.

The same dynamic range limitations occur in television. When the contrast is turned up too high, the highlights become white-on-white and the shadows become black-on-black. The midtones are well separated and distinct and may be pleasing to the observer who does not like information in the shadows or in the highlights. Others would complain.

Figure 9 shows signals going into an audio or a video amplifier, each of which permits a maximum and minimum voltage swing somewhat less than the swing of the amplified signal. As a result, at the output, both signals exhibit flat tops and flat bottoms which mean that some of the high frequency information (detail) is completely lost due to the large amplitude, low frequency information (large area differences)—too much gain.

AVC AND DODGING

In the early days of radio violent changes in volume would occur when tuning from one station to another, indicating that some were nearby and others far away. Since the listener was more interested in the program than in the distance to the transmitter, he could and did adjust for the large difference in signal level by using his volume control. In modern radios, these discomforts are eliminated by a simple feedback circuit called automatic volume control (*AVC*). This circuit (Figure 10) takes a sample of the amplified output, feeds a signal back to the input to govern its size. This is inverse feedback and is employed almost everywhere in electronics as a means of stabilizing output signals in the presence of wildly fluctuating input signals.

The response of the *AVC* circuit is deliberately kept slow so that only the low-frequency fluctuations are eliminated at the final output. If response of the feedback loop were as fast as the highest audible frequency, and if the amount of the feedback were 100%, then no signal at all would come out regardless of what went in. However, the response is kept slow, relative to the audible frequencies, and the amount of feedback is kept less than 100% to preserve the dynamics of music, etc.

In Figure 10, a high frequency signal with a low frequency average is fed into an amplifier employing AVC. The audible frequencies are filtered out of the feedback loop, allowing only the low-frequency variation to be fed

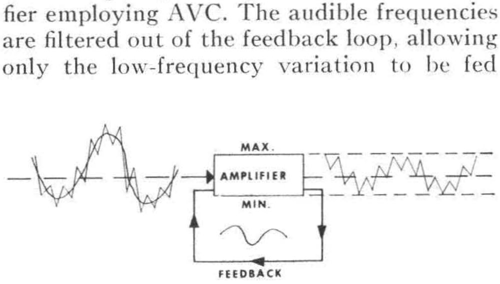

FIG. 10. Amplifier with frequency limited inverse feedback (AVC).

back. The resulting output shows large amplitudes at the audible frequencies but a much reduced amplitude in the subaudible frequencies. Although it is true that some of the information in the incoming signal has been suppressed (changes in volume) it is also true that this kind of information is generally trivial—and seldom related to the program material. In exchange for this loss, the listener has a better idea of what is going on back at the studio, and is being spared the extraneous information about the distance to this or that transmitter, how many kilowatts the station has, atmospheric disturbances, changes in his own line voltage, etc.—a net gain in useful information.

In photographic printing, there is the same opportunity to select the gain between the input-signal (negative) and the output-signal (print). Here, volume control may take the form of selecting a particular printing emulsion, or a particular color of light with which to print, or a particular amount of development after exposure. As before, the dynamic range of the amplifier is limited. If a contrasty grade of paper is chosen, having a high gain (gamma) there likely will be a saturation in the highlights and in the shadows, producing either black-on-black or white-on-white instead of what was in the negative in those areas. On the other hand, if a low gain paper is chosen it will limit the dynamic range of the output signal, and at the same time limit the amplitude of the high-frequency signals (detail) for which amplification is desired. A good laboratory technician can guess where to set the gain (grade of paper) for each incoming negative and will produce a reasonable assortment of output prints. However, a better technician will realize that—as he looks first at one area and then at another of the same print—different exposures are required for the best results. In other words, as he visually tunes from one program to another, he would like to adjust the volume. This he can do, and does, in the darkroom.

This is called dodging which (at one time) was accomplished by either attenuating the light with a fast-moving opaque device or by selectively extinguishing parts of the light source. Certain kinds of information in the input signal failed to reach the output. Again, this proved to be trivial information which might have told the interpreter that it is brighter on the sunny side of a hill than on its shady side, that the camera lens was vignetting at the corners, that it is darker in the shade of a cloud than in the bright sunlight, etc.

Such information yields nothing about the program one is trying to tune in (detail on the ground); to amplify it would only use up the limited dynamic range of our amplifier. And so, the experienced technician has for years been discarding this kind of trivia. In other words, he has suppressed the low frequencies (brightness differences) in order to allow his high frequencies (detail) to be fully amplified.

In modern printers, LogEtronic for example, dodging is performed automatically—using the same basic concepts as automatic volume-control in radio. Low-frequency variations of the input-signal (negative) are fed back and prevented from reaching the final output (print). As described in more detail elsewhere, the light source is a cathode ray tube whose image is projected through the negative onto the printing material. Light, after passing through the negative, is sampled by a phototube whose output signal is fed back to the cathode ray tube for instantaneous control of its brightness. As a consequence, a positive luminous image of the negative is formed on the face of the cathode ray tube which tends to suppress wild increases in volume (average brightness) in thin parts of the negative, and also tends to boost the volume (average brightness) in dense parts of the negative. Since the scanning spot is much larger than the finest detail which can be photographically recorded, it serves as a filter to prevent the feedback loop from explicitly operating on the high-frequency information.

Figure 11 shows a signal representing an input negative. The signal consists of high-frequency "pips" superimposed on a low-frequency ramp function. In (*a*), it is printed onto a high-contrast emulsion, producing a flat top and bottom devoid of detail. In (*b*), it is printed on a low-contrast emulsion which accommodates the low-frequency excursion but, at the same time, reduces amplitude of the high-frequencies by a corresponding amount. In (*c*), it is reproduced with automatic dodging which suppresses the low-frequency ramp, but once again on high-contrast emulsion, achieves maximum amplification of the high-frequency (detail) information. (Compare Figures 12(a), (b), and (c).)

The sine-wave response curve can also demonstrate the effect of automatic dodging or of unsharp masking—both being forms of inverse feedback with limited frequency response. Figure 13 shows the response of a printing system—optics and emulsion—without masking, as a function of image contrast

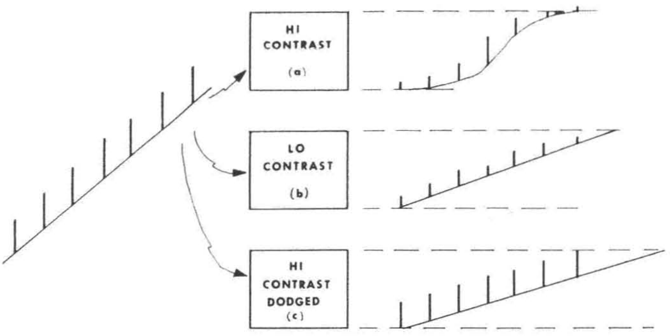

FIG. 11. Negative (ramp with pips) printed at High Contrast (a) Low Contrast (b) and High Contrast with automatic dodging (c).

versus image size (frequency). The unsharp mask has the opposite polarity, less contrast and cuts off at a lower frequency. The masked positive curve represents the sum of these two curves and illustrates how contrast of low-frequency images is reduced without affecting the high-frequencies—giving a flatter response with the general appearance of greater bandwidth.

It is worth noting that a single cycle (bit) of low-frequency information is only as informative as a single cycle (bit) of high-frequency information. Consequently, when there is discarded a single cycle of low-frequency information in exchange for better amplification of billions of cycles of high-frequency information, the picture is worth more than Confucius dreamed of.

TRANSFER CHARACTERISTIC AND D-LOGE CURVE

The transfer characteristic of any amplifier is the point-by-point relationship between its input and its output. In a vacuum tube, it is a plot of plate current versus grid voltage. For a cathode ray tube, it is spot brightness versus beam current. For a photographic material it would be density versus logarithm of the exposure. In each case, a specific curve represents a unique output value for a given input value. The ideal for any amplifier is a transfer characteristic consisting of a straight line which passes through zero. In electronics, this is seldom achieved and in photography it is not even approached. A curve having the shape of an *S* is always confronted. In the toe and the shoulder of the curve, the output is relatively insensitive to any changes in the input. Consequently, electronic circuits are always designed to operate on the straight line portion, hoping that the input signal will never get so big that it will cause the output to reach the toe or shoulder. Or, in a clever circuit, operation on the straight line portion is guaranteed by means of an automatic volume control.

Figure 14(a) shows an input signal consisting of a high-frequency (space or time) distribution superimposed on a low-frequency signal. If each point of this signal is projected vertically to the *S* shaped transfer characteristic curve, then horizontally to the corresponding space or time, there will be seen the exact shape of the output signal. Note that those points which were reproduced on either the toe or the shoulder of the curve are reduced in amplitude when compared with information which has been reproduced on the straight line, and steeper, portion of the curve. However, if it is assumed that the low frequency component has been suppressed by either automatic volume control or by automatic dodging then Figure 14(b) will show point-by-point where the remaining high-frequency information will be reproduced. Note that all of the high-frequency information has been restricted to the straight line portion of the curve where it receives the greatest amplification.

FAITHFUL REPRODUCTION

The question of whether or not faithful reproduction has taken place involves comparison between the reproduction and the original. In high-fidelity sound systems the comparison is made between sounds which come out of a loudspeaker compared to sounds which existed in the recording studio. During recording, the amplitude of low-frequency sounds are suppressed so that the needle does not overrun the groove. At playback, the pickup cartridge and the loudspeaker each have their own deficiencies in linearity and in frequency response. In the middle of this whole chain is the amplifier—the only element which can be built with good linearity and flat frequency response. However, in a good system it will be found that the amplifier

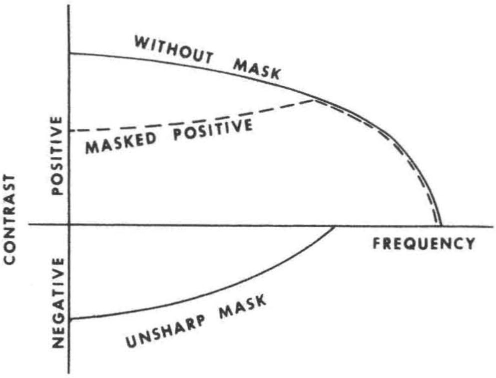

FIG. 13. Contrast versus space frequency curves with and without masking.

usually contains more distortions than any other single element in the system. These distortions are built-in on purpose, to compensate for the combined distortions of all the elements which precede and follow. The important thing is that the final result, after cascading all distortions, gives a good tonal reproduction of the sounds in the recording studio.

The same is true of tonal reproduction in photography. Others have pointed out the effects of haze in aerial photography. The effect of lens flare is similar. The nonlinear characteristic of every photographic emulsion is well-known. Here again there is found a whole chain of elements, each capable of distorting the relative values of brightness in the original scene.

In addition, there is the question whether faithful reproduction should be measured in terms of how the *camera* views the scene or how an *observer* views it. When a scene is surveyed, the eyes move from highlight to shadow to midtone, etc. While scanning, the iris of the eye is automatically and involuntarily opened or closed to accommodate for the local brightness. Unconsciously, search is made for detail everywhere in the scene and the average brightness of a particular region is ignored. Unfortunately, the camera is not as well endowed. Thus, the camera itself is the first source of distortion in photography. As

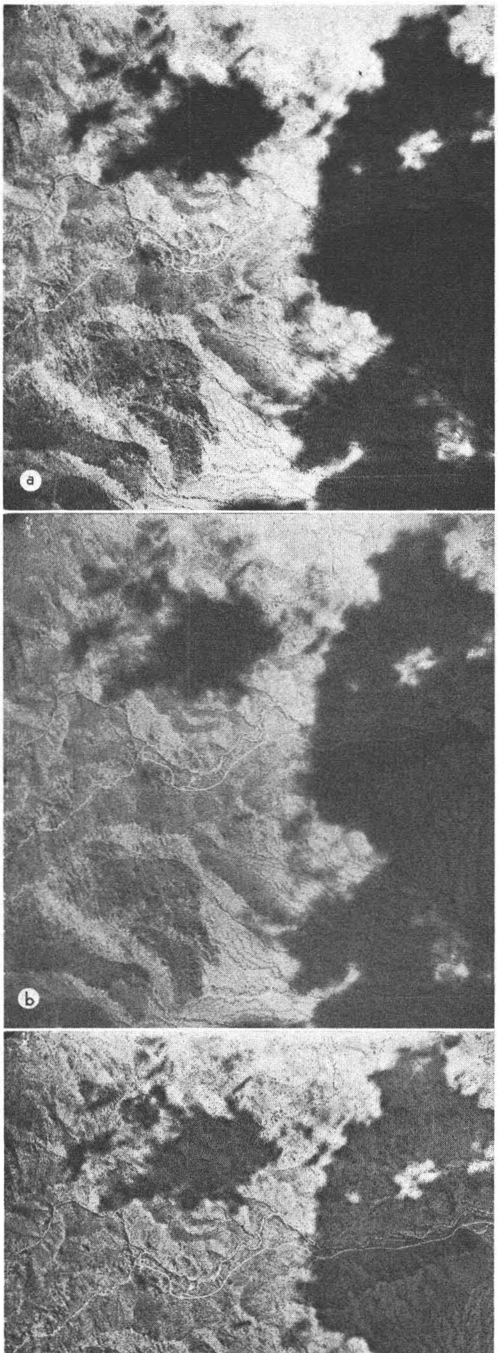

FIG. 12. Pictorial demonstration of the effects of no feedback and inverse feedback. Print (a) corresponds to 11(a) High Contrast—No feedback. Print (b) corresponds to 11(b) Low Contrast—No feedback. Print (c) corresponds to 11(c) High Contrast—With feedback.

might be expected, the effect of haze, lens flare, nonlinear emulsion characteristics—all gang up in an attempt to completely eliminate detail in dimly lit regions (shadows) of a scene. The question of faithful reproduction then becomes a question of what two points in the system should be compared.

One viewpoint is that the final reproduction should be compared with the negative obtained in the camera—or that the positive should be a "mirror image" of the negative. Unfortunately, this completely neglects the preceding distortions already introduced by the emulsion characteristics, lens flare in the camera, haze between the camera and the object being photographed, and the inability of the camera to scan a scene and to discard the noninformative information regarding differences in average brightness between different parts of the scene.

The answer to tone-distortion (due to haze, lens flare and nonlinear emulsions) is not a linear printing material—but one which is distorted in the opposite direction. Tone-distortion due to the inability of the camera to scan and to compensate for brightness differences is easily solved by automatic dodging during printing. Having accomplished these two things, it is found that the photographic reproduction system does not contain a single element which is capable of faithful tone-reproduction. Instead, it consists of a cascade of elements—many with their own distortions and others with distortions of kind and amount which compensate for those which cannot be eliminated. Only under these conditions can the final reproduction begin to approach what the *observer* would see—truly faithful reproduction.

THE SP10/70

Retracing the development of the Log-Etronic continuous-strip printer Model SP10/70 might illustrate the value of "likeness" thinking.

The original version of the SP10/70 was built to demonstrate that automatic dodging and automatic exposure control could be achieved in a contact printer with the materials in continuous motion. Then, and even now, it was difficult to explain exactly what dodging does to a photograph. Early efforts attempted to explain the result in terms of the D-Log E curve, which unfortunately fails to distinguish between low-frequency contrast and high-frequency contrast. Although it was easy for an electronics engineer to understand that dodging is akin to automatic volume-control and that the photographic emulsion is merely a DC amplifier whose gain is equal to gamma, this explanation did not suffice for all. Neither was it sufficient to say that the picture had been run through a high pass filter, removing the low-frequency components and amplifying the remaining high-frequencies to whatever value was determined by the gain of the recording emulsion. Nevertheless, the pictorial results of automatic dodging have long been available for whatever word description best fits the need—many produced by the early SP10/70.

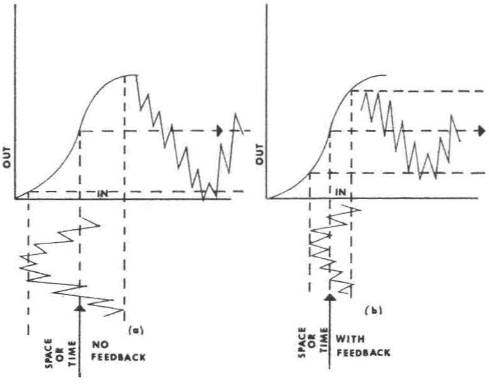

FIG. 14. Transfer characteristic showing output versus input signals without (a) and with (b) inverse frequency limited feedback as used in AVC, unsharp masking and automatic dodging.

While the practical advantages of automatic dodging were being demonstrated, the trend toward higher and higher altitudes for photography with the cry for higher and higher resolution began to exceed the threshold of perception. Then, the strip printers would regularly reproduce 30 or 40 lines-per-millimeter (good enough for most existing photography). However, "blue sky" goals of several hundred lines-per-millimeter suddenly became a recognized need. Up to that time just "fair" contact was deemed adequate since the light source was relatively collimated—having an entrance angle of approximately 60°. Realizing that resolution depends on spread function which in turn depends on both contact and on printer optics, optimizing was started. First, the roller system in the vicinity of the printing aperture was redesigned to allow minute linear adjustment—reducing slippage between materials to zero. Next, contact between materials was improved by transverse support of the negative (at first a pair of teflon strips, now a pair of stainless steel rollers). Finally, the anamorphic projection system was replaced by conventional spherical optics reducing the entrance angle down to approximately 10°.

While measuring the results of these changes, there became acutely evident their dependence on the emulsion (amplifier) used, the level of exposure (operating point) and the type of processing (second amplifier). As would be expected, best results were obtained with fine-grain (low-noise) emulsions developed to high-contrast (high gain) when exposed to a level where the target occupied midscale (Class A amplifier). Automatic dodging (AVC) insured that the operating point was optimum for the full length and width (all programs) of the film.

THE PAYOFF

Whereas the mental and physical processes of design are vital to the engineer, only the results impress the user. The current version of the strip printer, Model SP10/70A, is able to reproduce high-contrast resolution targets having 160 lines-per-millimeter, measured anywhere over the full width and length of film, when printed on *Recordak Micro-File, Type 5455*, at a rate of 20 feet-per-minute.

The longitudinal and transverse bars in the targets are equally well resolved, indicating that there is no slippage at all in the transport system. The bars do not merge, but tend to break apart, indicating that the system is not limited by the optics or mechanics of the printer, but instead by noise in the system (dust, scratches, etc., in the target, or grain in the recording emulsion). Under the right conditions of exposure and development, 200 lines-per-millimeter have been resolved. Using a target with 228 lines-per-millimeter, and assuming that the film can resolve 500 lines-per-millimeter, the resolution capability of the printer is calculated. Using the formula:

$$1/R^2 = 1/T^2 + 1/S^2 + 1/P^2$$

where:

R is the number of lines resolved in the final reproduction,
T is the number of well resolved lines in the target,
S is the resolution limit of the film, and
P is the resolution capability of the printer,

it is calculated that the printer is resolving well above 700 lines-per-millimeter. The spacing between such lines is only two wavelengths of blue light.

BILLIONS OF BITS-PER-MINUTE

The title of this paper will now be recognized as a way of introducing some of the language and concepts of the electronic world to those in the photographic world. Only the photographic communications' link is able to transmit billions of bits of information in a minute. The fastest of all, and with the shortest range, is the continuous strip-printer. An information transfer rate of approximately 30 billion bits-per-minute is possible in a strip-printer, operating at 20 feet-per-minute, on 9″ wide film with a resolving ability of 160 lines-per-millimeter. This figure is based on test results and represents the transfer rate of the whole system, including target, printer, emulsion and processing. The printer itself is calculated to do well above this figure.

At billions-of-bits-per-minute, representing that many "yes" or "no" answers to that many questions—one puzzling question is: Where do all the questions originate? Worse yet—how will all of the answers be handled?

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