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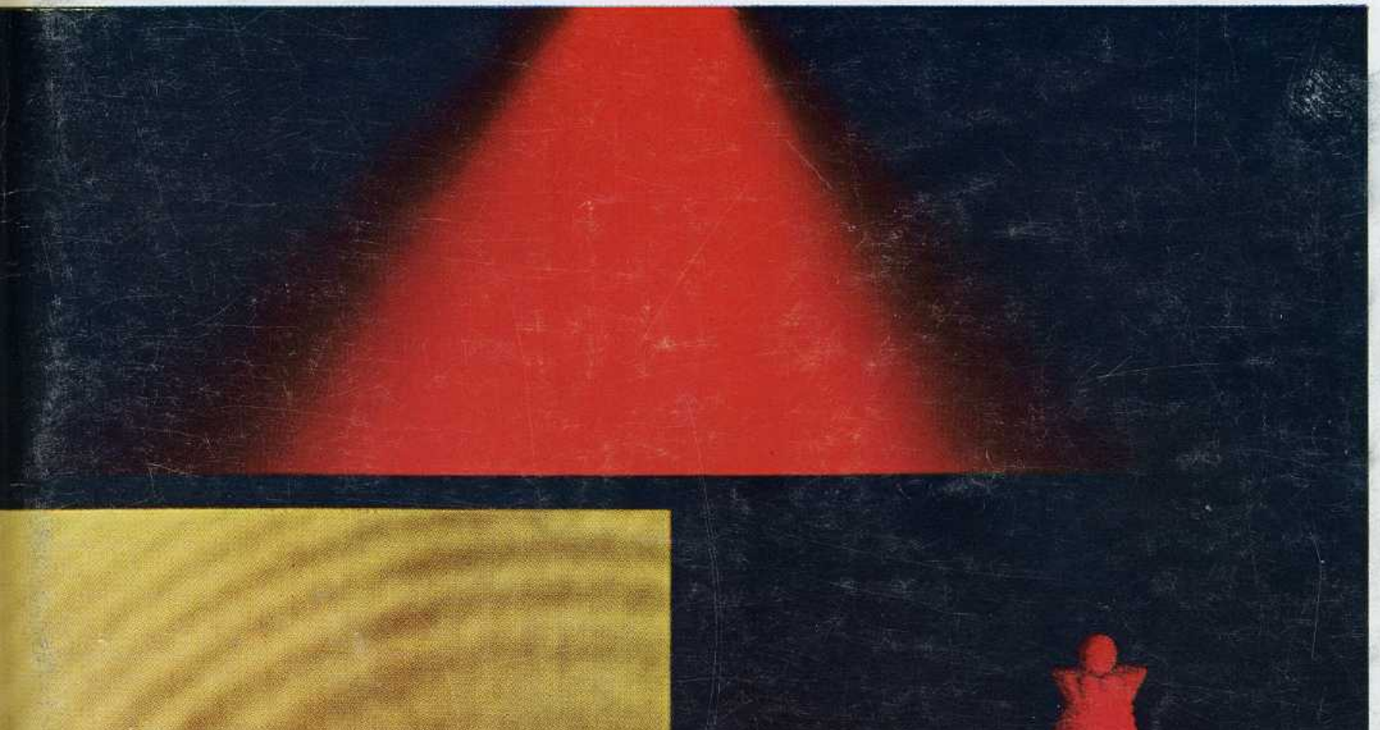

LASER PHOTOGRAPH

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Photography by Laser

The highly coherent light produced by the laser is used in a novel photographic process, in which the light-sensitive film, instead of recording an image, in effect records the light waves themselves

by Emmett N. Leith and Juris Upatnieks

In spite of the steady refinement of photographic techniques and the invention of new photographic materials, the optical aspects of photography have changed little over the past 100 years. Reduced to its essential elements the photographic process consists of recording an illuminated three-dimensional scene as a two-dimensional image on a light-sensitive surface. The light reflected from the objects in the scene is focused on the sensitive surface by some kind of image-forming device, which can be a complex series of lenses or simply a pinhole in an opaque screen [*see upper illustration on page 28*].

This article deals with a radically different concept in photographic optics. Invented less than 20 years ago, this process, which can be called photography by wave-front reconstruction, does *not* record an image of the object being photographed but rather records the reflected light waves themselves. The photographic record, a hodgepodge of specks, blobs and whorls, is called a hologram; it bears no resemblance to the original object but nevertheless contains—in a kind of optical code—all the information about the object that would be contained in an ordinary photograph and much additional information that cannot be recorded by any other photographic process.

The creation of an intelligible image from the hologram is known as the reconstruction process. In this stage the captured waves are in effect released from the hologram record, whereupon they proceed onward, oblivious to the time lapse in their history. The reconstructed waves are indistinguishable from the original waves and are capable of all the phenomena that characterize the original waves. For example, they can be passed through a lens and brought to a focus, thereby forming an image of the original object—even though the object has long since been removed! If the reconstructed waves are intercepted by the eye of an observer, the effect is exactly as if the original waves had been observed: the observer sees what to all appearances is the original object itself in full three-dimensional form, complete with parallax (the apparent displacement of an object when seen from different directions) and many other effects that occur in the normal "seeing" process.

The wave-front reconstruction process was discovered in 1947 by Dennis Gabor of the Imperial College of Science and Technology in London. During the next few years Gabor developed the method systematically, emphasizing particularly its applications to electron microscopy. Many other workers throughout the world have since made significant contributions—notably Hussein M. A. El-Sum and Paul Kirkpatrick of Stanford University—but their efforts were hampered by the lack of an adequate source of coherent light, that is, light whose waves are all in phase. The invention of the laser in 1960 opened the way to new advances in wave-front reconstruction photography. Using a gas laser as a source of coherent light, as well as several other previously untried techniques, we have been able to obtain high-quality, three-dimensional hologram images in our laboratory at the University of Michigan. Partly as a result of our work and partly as a result of the largely unexplored potential of the laser as a source of coherent light, there has been a widespread resurgence of interest in the possible uses of this intriguing photographic process.

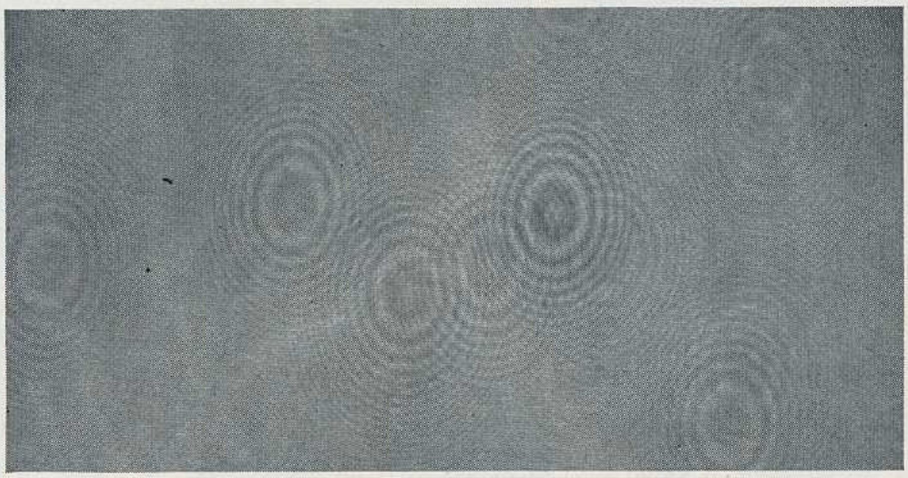
The basic optics of wave-front reconstruction photography differ from those of ordinary photography in three main respects. As in ordinary photography, the object is illuminated and a photographic plate is positioned so as to receive light reflected from the object. Unlike ordinary photography, however, no lens or other image-forming device is used and consequently no image is formed. Instead each point on the object reflects light to the entire photographic plate; conversely, each point on the plate receives light from the entire object [*see top illustration on page 29*]. The second departure from ordinary photography is the use of coherent light for illuminating the object, and the third is the use of a mirror to beam a portion of the coherent light directly to the plate, bypassing the object. This beam is called the reference beam, and it produces, by means of interference effects, a visible display of the wave pattern of the light impinging on the plate from the object; what is recorded on the plate is the resulting interference pattern.

Reflected light waves, like any other waves, are described by their amplitude (or intensity) and by their phase (or frequency). In the case of a point scatterer of light, the reflected waves travel outward from their origin in a series of ever expanding spherical shells, called wave fronts, that are concentric around the point of origin. These spherical waves are the three-dimensional analogue of the circular waves that appear on the surface of a still pond when a stone is dropped into the water. If the reflecting object is not a single point but a complex object, it can then be regarded as a collection of a large number of points, and the resulting wave pattern reflected from the surface of the object can be regarded as the sum of many such sets of spherical waves, each set concentric about its point of origin [*see top illustration on page 30*]. The exact form of the wave pattern reflected from an extended and irregular object is highly complex and cannot be described in detail here.

The central problem of wave-front reconstruction photography is to record this complex, signal-bearing pattern as it exists at a given plane at some instant of time. Such a record can be thought of as a "freezing" of the wave pattern; the pattern remains frozen until such time as one chooses to reactivate the process, whereupon the waves are "read out" of the recording medium. To capture the wave pattern completely both the amplitude and the phase of the waves must be recorded at each point on the recording surface. Recording the amplitude portion of the waves poses no serious problem: ordinary photographic film records amplitude by converting it to corresponding variations in the opacity of the photographic emulsion. The emulsion is entirely insensitive to phase relations, however, and one must assemble some appropriate apparatus that can convert these phase relations into a form in which they can be recorded photographically.

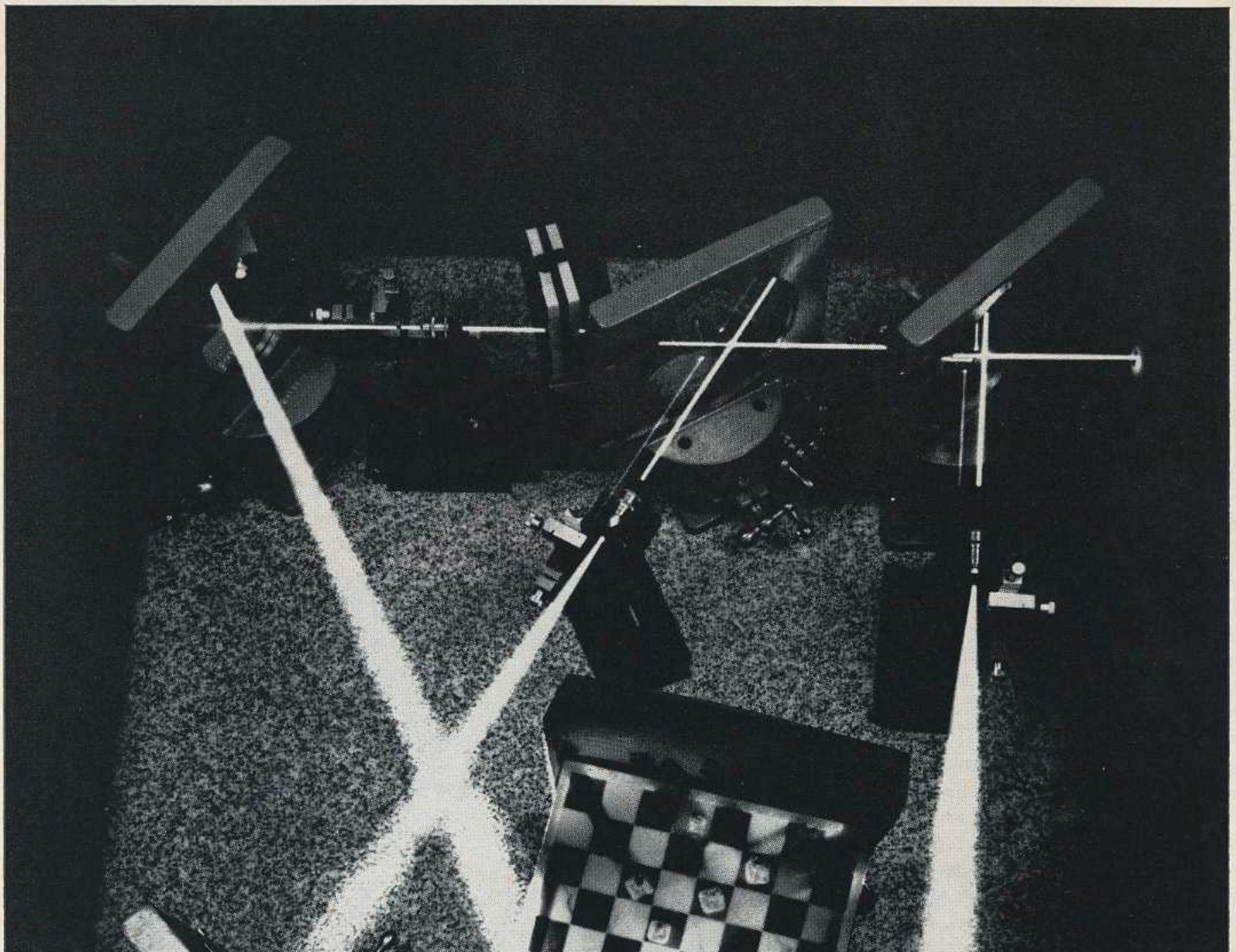
In wave-front reconstruction photography the phase relations are rendered visible to the photographic plate through the technique of interferometry, a standard and long-established way of converting phase relations into corresponding amplitude relations. We shall first consider how this is done in the comparatively simple case in which two

ORDINARY PHOTOGRAPH was made by illuminating a chessboard and a group of chessmen with normally incoherent light and recording a two-dimensional image of the scene on photographic film. Light reflected from chessmen is focused on film by camera lens.



HOLOGRAM RECORDING of the scene shown in photograph at top of page was made in the first stage of the process of wave-front reconstruction photography. The visible structure of the hologram bears no resemblance to the original scene but nevertheless contains more information about the scene than would be contained in an ordinary photograph. The holograms used in this article were made by Albert Friesen of the University of Michigan.

RECONSTRUCTED IMAGE was made by directing a laser beam through the hologram. The reconstructed waves were then passed through a lens and brought to a focus, thereby forming an image of original scene, even though chessmen had long since been removed.



PHOTOGRAPHIC EQUIPMENT used in the first stage of the wave-front reconstruction process was photographed in the authors' laboratory at the University of Michigan. The laser beam enters from right at top and immediately passes through two partially reflecting and partially transmitting glass plates. The reflected parts of the beam are again reflected from two mirrors (*bottom left and right*) before being used to illuminate the chessboard (*center*). The transmitted part of the beam, called the reference beam, is reflected from another mirror (*top left*) and then impinges directly on the hologram plate (*sandwich-like object at bottom center*). Each beam passes through a microscope lens, which broadens the beam but has no effect on its valuable coherence properties.

collimated light beams, whose wave fronts are successive planes perpendicular to the direction of the beams, interact to form a characteristic interference pattern; in terms of the shape of their wave fronts such waves are referred to as plane waves.

If two plane waves derived from a common source impinge at different angles of obliquity on an opaque surface, they will produce a set of uniform, parallel interference fringes on the surface. The spacing of the fringes will depend solely on the angle between the waves. At some places on the surface the waves will arrive in phase and their amplitudes will add to produce a resultant light intensity greater than would be produced by either wave acting alone. This process is called constructive interference and is responsible for the light fringes in the interference pattern. At other places the waves will arrive out of phase and will tend to cancel each other, the cancellation being complete if the two waves are of equal amplitude. This process is called destructive interference and is responsible for the dark fringes in the interference pattern. Where the waves are neither in nor out of phase, the resultant light intensity and corresponding fringe tone are intermediate between these two extremes.

A photographic recording of such a fringe pattern will yield a grating-like structure that can be regarded as a two-dimensional analogue of the sinusoidal wave produced by an electric oscillator. The important point of this analogy is that just as an electric wave can be modulated to serve as a carrier of information (about sound, say), so can the interferometrically produced wave pattern be modulated to serve as a carrier of information about the light waves that produced it.

Modulation of any kind of carrier wave can be accomplished in various ways, but the best-known and most commonly used methods are amplitude modulation (AM) and frequency modulation (FM). In amplitude modulation information is imposed on the carrier wave by causing the wave's amplitude to vary in accordance with some lower-frequency wave [*see illustration on page 31*]. In frequency modulation the amplitude of the carrier wave remains constant but the spacing between the various cycles is altered. The effect can be described as a change in frequency: at some positions the cycles are compressed and the frequency is correspondingly increased, whereas at other positions the cycles are expanded and the frequency is decreased. This kind of modulation can alternatively be described as phase modulation, since at any given time the phase, or the relative positions of the wave crests and troughs with respect to some stationary point, is different from what it would be in the absence of the modulation. (Although frequency modulation and phase modulation are not quite identical, the technical distinctions are not important here and will be disregarded.)

When the irregular wave pattern reflected from a complex object is made to interfere with a plane wave, the resulting interference pattern, instead of being uniform, has an irregularity that is related to the irregularity of the impinging wave fronts. At places where the signal-bearing waves have their greatest amplitude the interference fringes have the greatest contrast, whereas at places of low signal-wave amplitude the fringe contrast is low. Thus variations in the amplitude of the waves reflected from the object produce corresponding variations in the contrast of the recorded fringe pattern.

As we have noted, the spacing of the fringes is related to the angle between the signal-bearing waves and the reference waves. At places where the signal-bearing waves make a large angle with the reference waves the resulting fringe pattern is comparatively fine; at places where the waves meet at lesser angles the fringe pattern is coarser. Therefore the variations in the phase of the signal-bearing waves produce corresponding variations in the spacing of the fringes on the photographic record.

In brief, we have made two significant observations: both the amplitude and the phase of the signal-bearing waves can be preserved respectively as modulations in the contrast and spacing of the recorded interference fringes. All the information that can be carried by the light waves reflected from the object can be recorded on the interference grating produced by making these waves interfere with an obliquely impinging plane wave.

A hologram made in the manner just described has many of the properties of a grating produced on a ruling engine, but there are several important differences, the most important of which is the nonuniformity of the hologram grating slits as opposed to the precise uniformity attained in high-quality ruled gratings. Whereas the inadvertently produced irregularities in an imperfectly ruled grating give rise to false spectral lines, called "ghosts," the deliberately induced irregularities in a hologram give rise, in the reconstruction process, to a complete, well-defined image.

When a grating consisting of uniformly spaced opaque and transparent slits is illuminated with a collimated beam of monochromatic light, a number of plane waves are generated by the interaction of the light with the grating structure [*see right side of top illustration on page 32*]. These plane waves are radiated at various angles, which are determined by the spacing of the slits in the grating. The "zero order" wave propagates in the same direction as the incident wave and can be regarded as an attenuated version of the incident wave. In addition, there are the two "first order" diffracted waves, one on each side of the zero-order wave. Beyond these occur the second-, third- and higher-order diffracted waves.

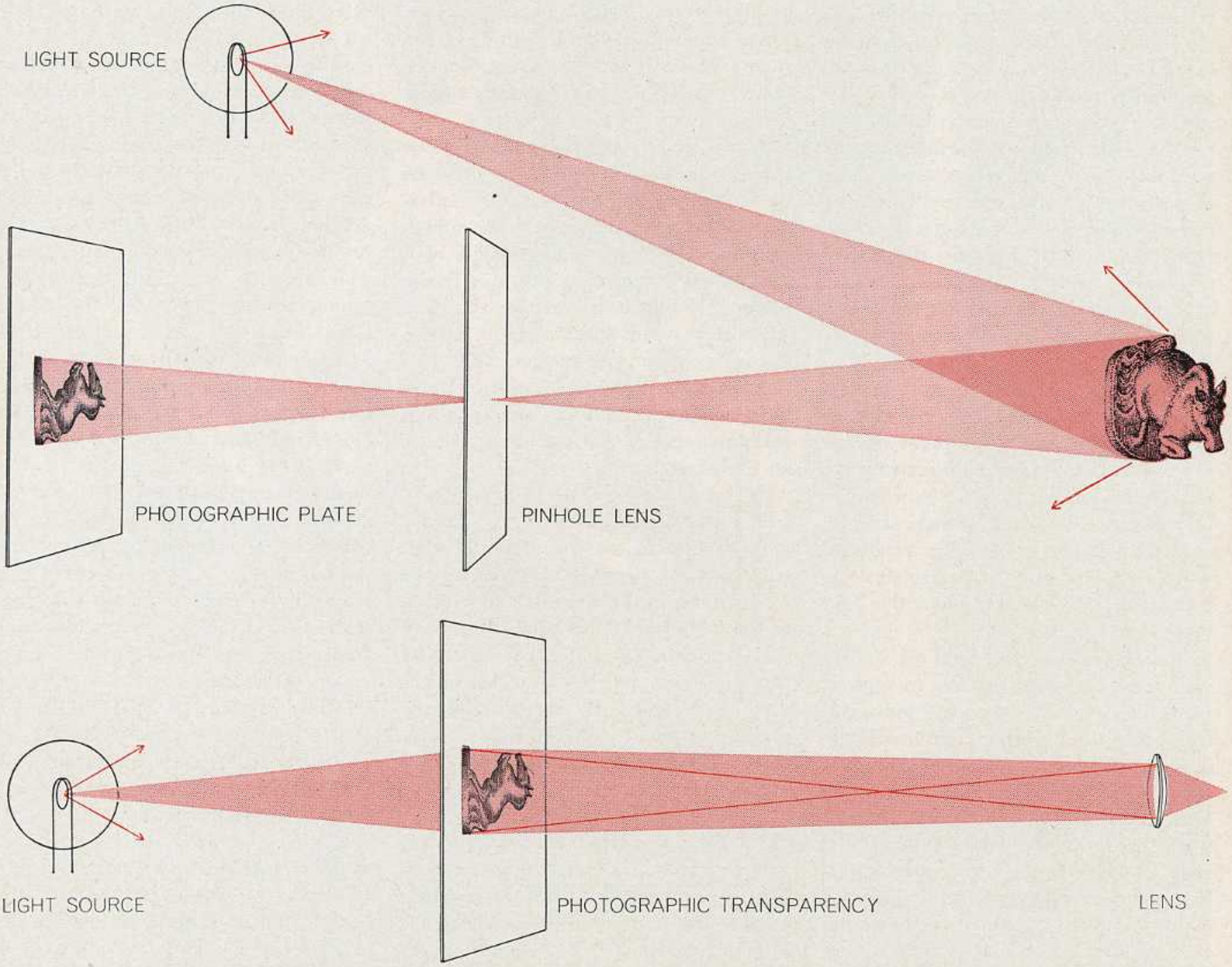
The generation of these diffracted waves can readily be explained by regarding the transparent slits as original sources, each radiating cylindrical waves. These elemental waves reinforce each other in certain directions, thereby giving rise to the various diffracted orders. The directions of reinforcement are obtained by drawing tangent lines to the various elemental wave fronts. The zero-order wave is formed by combining all the wave fronts that originated from the slits at the same time and are therefore all equidistant from the surface of the grating. By drawing a line tangent to all these corresponding cylindrical wave fronts the zero-order wave is obtained. This wave is parallel to the grating surface. One of the first-order diffracted waves is constructed by combining an elemental wave front from one slit with the previous wave front from the adjacent slit, then combining that with a still more previous wave front from the next adjacent slit, and so on. The other first-order diffracted wave is constructed in a similar way but in the opposite direction. The second-order diffracted waves are constructed by combining, from adjacent slits, wave fronts that are two wavelengths apart, and so on. From this construction method it is apparent that the closer the spacing of the grating lines, the greater the angle of diffraction.

When the spacing, or phase, of the grating slits is irregular, with some regions having closer line spacings than other regions, the localized variations in spacing give rise to corresponding local variations in the direction of the diffracted waves. Similarly, local variations in the contrast, or amplitude, of the fringes produce local variations in the amplitude, or intensity, of the diffracted wave. Thus the diffracted wave front is perturbed in a way that is related in a simple and predictable manner to the irregularities, both in spacing and contrast, of the hologram fringe pattern.

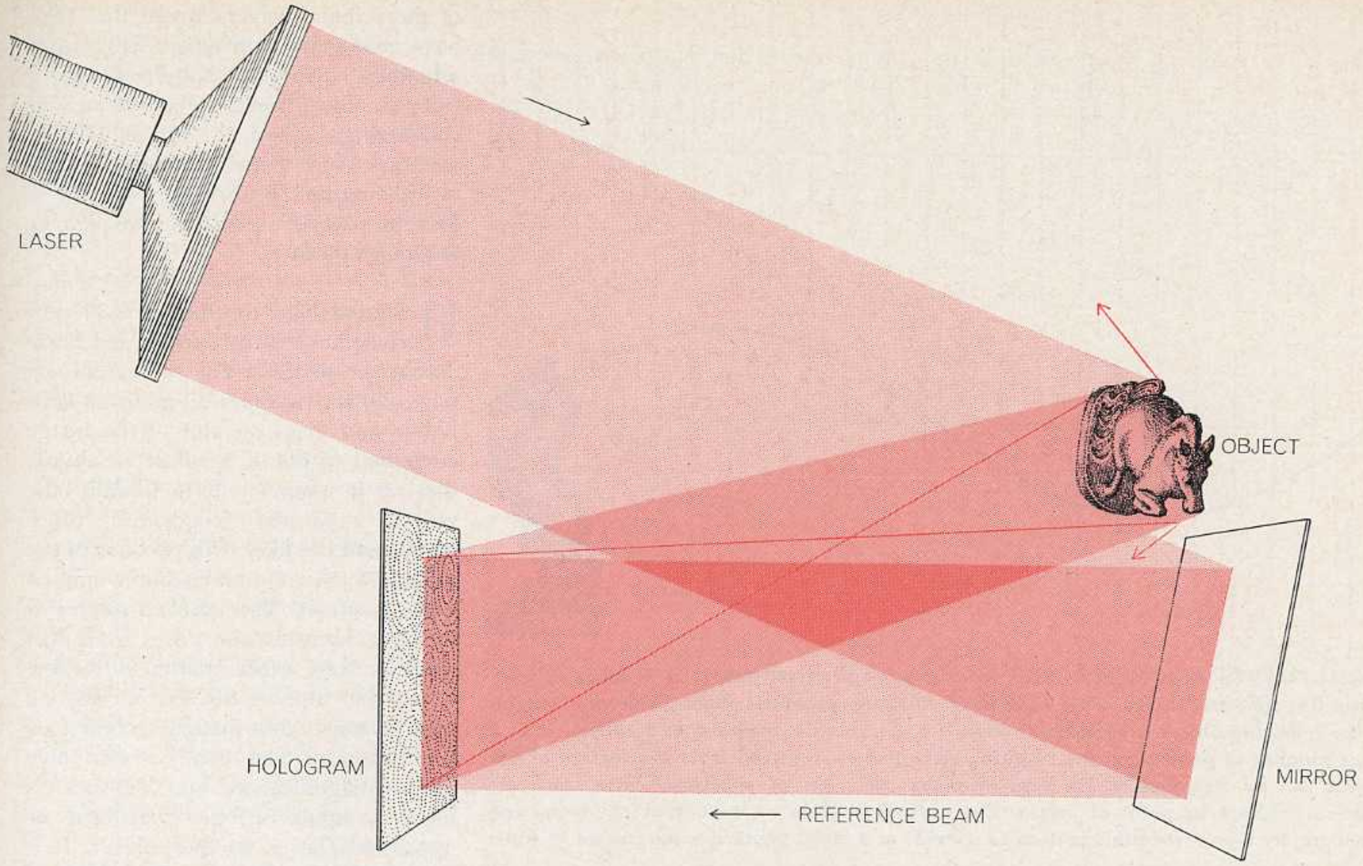
The reader will recall, however, that these fringe irregularities were produced by local variations in the amplitude and direction of the signal-bearing wave fronts that impinged on the hologram plate when the hologram was recorded. There is a kind of reversibility here: the distortions of the diffracted wave fronts by the fringe irregularities are precisely those distortions on the original wave front that gave rise to the fringe irregularities. For example, it was pointed out in the discussion of hologram construction that places where the signal-bearing wave fronts made the greatest angle with the reference wave front corresponded to the most closely spaced fringes. These areas of the hologram grating in turn diffract light at greater angles.

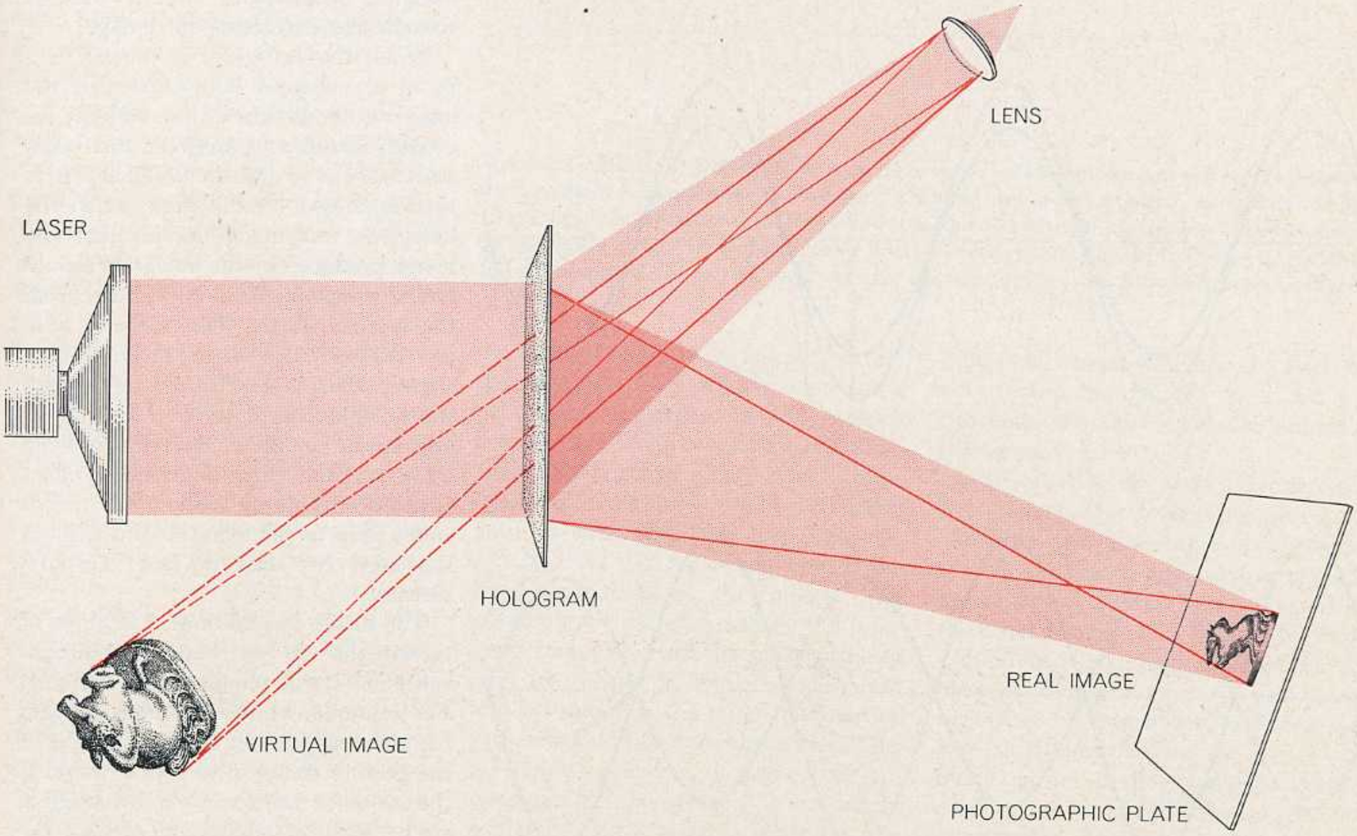
Indeed, the manner of constructing the diffracted orders from the hologram diffraction grating is essentially the inverse of the process of constructing the interference pattern that is recorded on the hologram. The similarity of the two processes is true on a much more rigorous basis than we have described here and is the key concept underlying the wave-front reconstruction process. The two sets of first-order diffracted waves produced by the hologram are each an exact replica of the waves that issued from the original object. These waves propagate outward from the hologram, behaving in all respects as the original waves would have done had they not been interrupted by the photographic plate placed in their path. A lens placed in the path of the diffracted waves can bring them to a focus, thereby forming an image of the original object, even though the original object is no longer present.

The two first-order waves differ from each other in one important respect. One diffracted order consists of waves that, when projected back toward the illuminating source, seem to emanate from an apparent object located where the original object was located. We say that these waves produce a virtual image, similar to the virtual images seen in a mirror. The other first-order diffracted waves are also accurate replicas

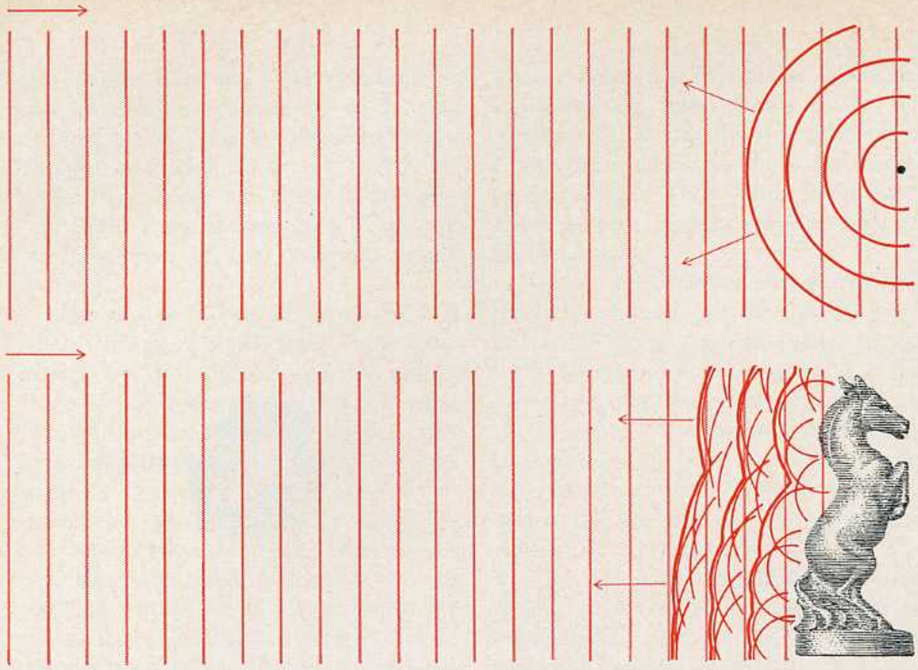


DIFFERENCES between ordinary photography and photography by wave-front reconstruction are illustrated schematically on these two pages. Ordinary photography consists of recording an illuminated three-dimensional object as a two-dimensional image on a light-sensitive surface (*top left*). The light reflected from the object is focused on the surface by some kind of image-forming device, which may be simply a pinhole in an opaque screen. When ordinary incoherent light is shone through the photographic transparency (*bottom left*), the eye sees only a static, two-dimensional image of the original object. In the recording stage of wave-front reconstruction photography (*top right*) no lens or other image-forming device is used and consequently no image is formed. Instead each point on the object reflects light to the entire hologram; conversely, each point of the hologram receives light from the en-

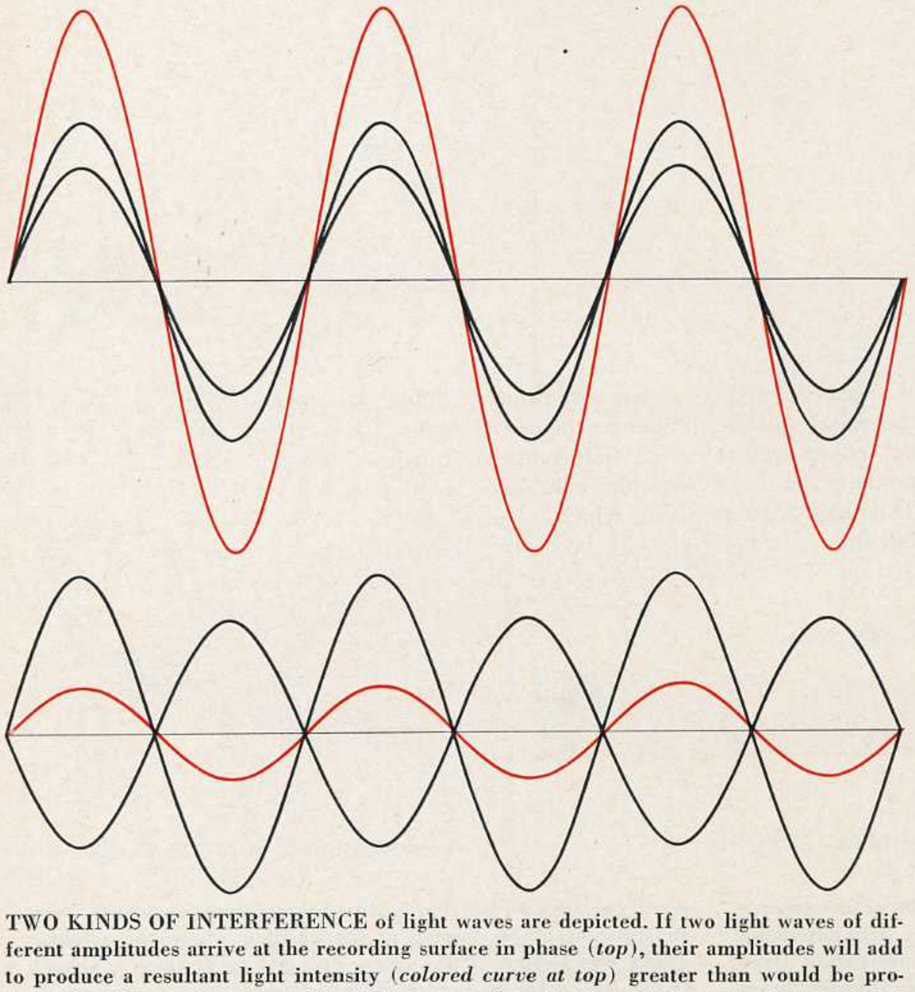




tire object. The reference beam produces, by means of interference effects, a visible display of the wave pattern of the light impinging on the hologram from the object. In the reproduction stage (*bottom right*) the hologram is illuminated with a collimated beam of monochromatic light and two images are produced by the "first order" diffracted waves emerging from the hologram interference grating. One diffracted order consists of waves that, when projected back toward the illuminating source, seem to emanate from an apparent object located at the position where the original object was located. These waves are said to produce a virtual image. The other first-order diffracted waves have conjugate, or reversed, curvature. These waves produce a real image, which can be photographed directly, without the need for a lens, by simply placing a photographic plate at the position of the image.



LIGHT WAVES ARE REFLECTED from a point scatterer (*top*) in a series of ever expanding spherical shells, called wave fronts, that are concentric about the point of origin. If the reflecting object is complex (*bottom*), it can then be regarded as a collection of a large number of points, and the resulting wave pattern reflected from the surface of the object can be regarded as the sum of many such sets of spherical waves, each set concentric about its point of origin. The central problem of wave-front reconstruction photography is to record this pattern as it exists at a given plane at some instant of time.



TWO KINDS OF INTERFERENCE of light waves are depicted. If two light waves of different amplitudes arrive at the recording surface in phase (*top*), their amplitudes will add to produce a resultant light intensity (*colored curve at top*) greater than would be produced by either wave acting alone. This process is called constructive interference and is responsible for the light fringes in the interference pattern. If the light waves arrive out of phase (*bottom*), their amplitudes will tend to cancel one another. This process is called destructive interference and is responsible for the dark fringes in the interference pattern.

of the original waves, except that they have conjugate, or reversed, curvature: originally diverging spherical waves from an object point are converted into converging spherical waves. These waves produce a real image, which can be photographed directly, without a lens, by placing a photographic plate at the image position.

Holograms and the images they produce have many curious and fascinating properties. The hologram on page 25, for example, is quite unintelligible and gives no hint of the image embodied within it. A cursory examination of it tempts one to identify the visible structures (concentric rings, specks and the like) with portions of the subject. Such an identification would be quite incorrect. The visible structure is purely extraneous and arises from dust particles and other scatterers on the mirror that supplies the reference beam. The pertinent information recorded on the hologram film can be seen only under magnification and consists of highly irregular fringes that bear no apparent relation to the subject. It is quite unlikely that one could learn to interpret a hologram visually without actually reconstructing the image.

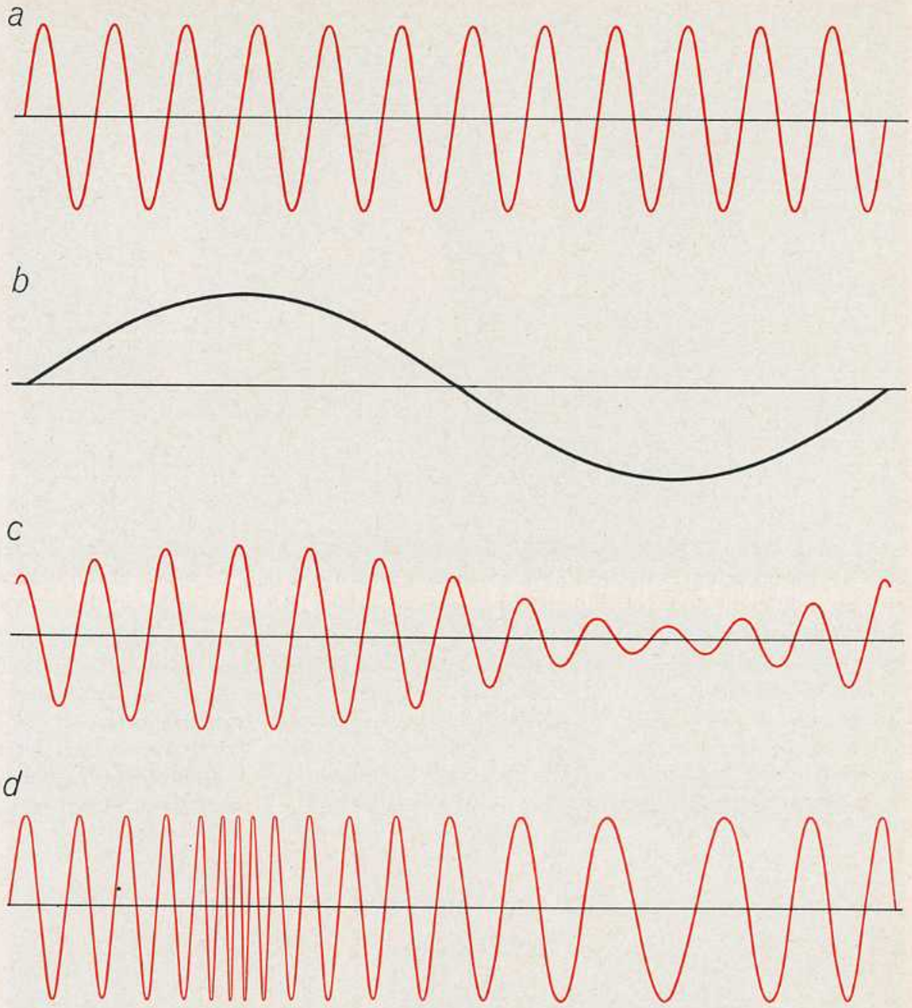
When the hologram is placed in a beam of coherent light, however, the images embodied in it are suddenly revealed. The identity between the reconstructed waves and the original waves that impinged on the plate when the hologram was made implies that the image produced by the hologram should be indistinguishable in appearance from the original object. This identity is in fact realized. The virtual image, for instance, which is seen by looking through the hologram as if it were a window, appears in complete, three-dimensional form, and this three-dimensional effect is achieved entirely without the use of stereo pairs of photographs and without the need for such devices as stereo viewers.

The image has additional features of realism that do not even occur in conventional stereo-photographic imaging. For example, as the observer changes his viewing position the perspective of the picture changes, just as it would if the observer were viewing the original scene. Parallax effects are evident between near and far objects in the scene: if an object in the foreground lies in front of something else, the observer can move his head and look around the obstructing object, thereby seeing the previously hidden object. Moreover, one must refocus one's eyes when the observation is changed from a near to a more distant object in the scene. In short, the reconstruction has all the visual properties of the original scene, and we know of no visual test one can make to distinguish the two.

Similarly, the real image can be viewed by an observer, who will find it suspended in space between himself and the plate. This image has all the aforementioned properties, but it is somewhat more difficult to view, for reasons we shall not discuss here.

A hologram made in the manner just described has several interesting properties in addition to those having to do with the three-dimensional nature of its reconstruction. As an example, each part of the hologram, no matter how small, can reproduce the entire image; thus the hologram can be broken into small fragments, each of which can be used to construct a complete image. As the pieces become smaller, resolution is lost, since resolution is a function of the aperture of the imaging system. This curious property is explained on the basis of an observation made above: each point on the hologram receives light from all parts of the subject and therefore contains, in an encoded form, the entire image.

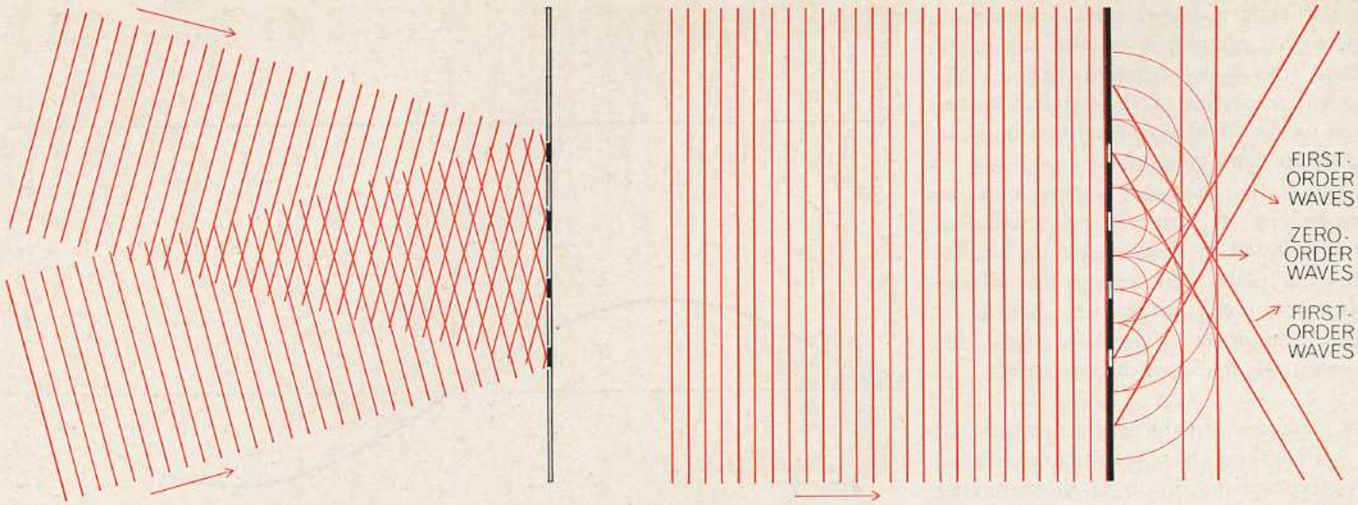
A second curious property of the wave-front reconstruction process is that it does not produce negatives. The hologram itself would normally be regarded as a negative, but the image it produces is a positive. If the hologram were copied by contact printing, the hologram would be reversed in the sense that opaque areas would now become transparent and vice versa. The image reconstructed from the copy, however, would remain a positive and would be indistinguishable from the image produced by the original except for the small degradation in quality that normally occurs in photographic copying. This curious property arises because the information is recorded on the film in the form of a modulated spatial carrier. Contact printing of the film results in only a reversal in the polarity of the carrier, and polarity reversals of a carrier do not affect the signal data contained on the carrier, a fact well known to electronic engineers. The reason for this insensitivity to polarity can be understood by recalling that the information on the grating carrier is embodied in the fringe contrast and in the fringe spacings; neither of these is altered by the reversal of polarity.



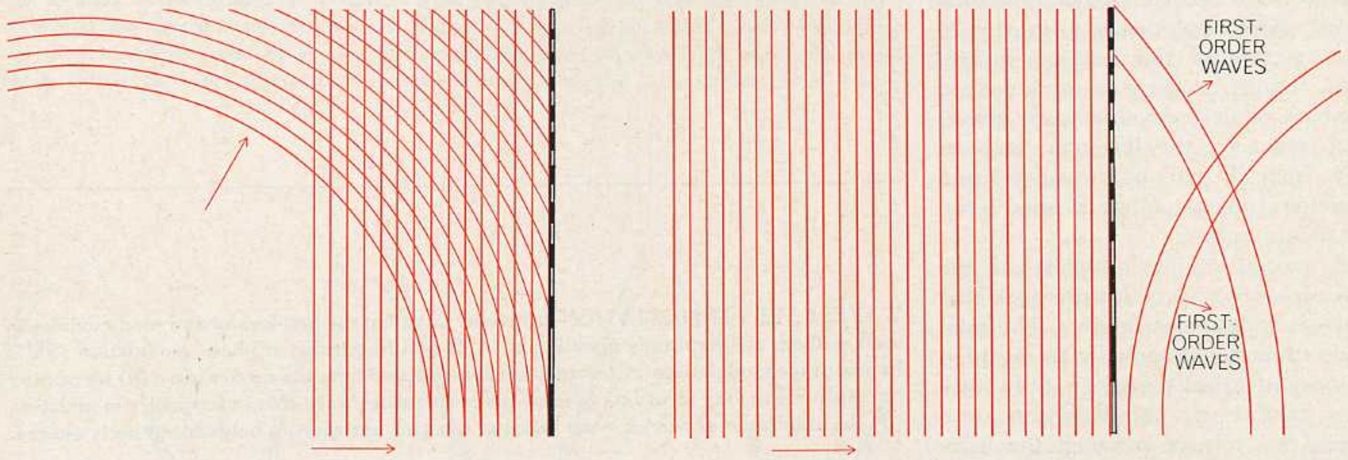
WAVES CARRY INFORMATION in various ways, but the best-known and most commonly used methods are amplitude modulation (AM) and frequency, or phase, modulation (FM). In amplitude modulation (*c*) information is modulated onto the carrier wave (*a*) by causing its amplitude to vary according to some lower-frequency wave (*b*). In frequency modulation (*d*) the amplitude of carrier wave remains constant but spacing between cycles is altered.

Another interesting property of wave-front reconstruction photography is that the reconstructed image has very nearly the same contrast rendition as the original object, regardless of the contrast properties of the photographic emulsion. Thus high-contrast plates, which in ordinary photography would be useful only for such objects as line drawings, can be used without losing any of the tonal properties of the object. The photographic plate containing the hologram may be capable of registering only two levels of density—transparent and opaque—but the tonal rendition of the reconstruction does not suffer. This mysterious property of wave-front reconstruction photography is not easily explained, but it is again related to the use of a carrier and also to the fact that each point on the object is recorded not on a single point of the hologram but on the entire hologram. Under these circumstances it can be shown that the failure to preserve a proper gray scale produces, as its main effect, higher-order diffracted waves. The first-order diffracted waves, which produce the reconstructed images, are to a first approximation unaffected by the distortion of the gray scale.

Still another interesting property of holograms is that several images can be superimposed on a single plate on successive exposures, and each image can be recovered without being affected by the other images. This is done by using a different spatial-frequency carrier for each picture, just as many radio messages can be transmitted between two sites simultaneously by the use of different carrier frequencies. The grating carriers can be of different frequencies, as in radio communication; moreover, since the film is two-dimensional there is still another degree of freedom, that of angle. Thus the grating carrier is specified both by the fringe spacing and by the fringe orientation. The fringe pattern can be vertical for one exposure, for example, and horizontal for another. In the reconstruction process the various



UNIFORM, PARALLEL FRINGES are produced by the interference of two plane waves derived from a common source and impinging at different angles of obliquity on an opaque surface (*left*). The spacing of the fringes depends solely on the angle between the waves. When the grating is illuminated with a beam of coherent light (*right*), a number of plane waves are generated by the interaction of the light with the grating. The "zero order" wave propagates in the same direction as the incident wave and can be regarded as an attenuated version of the incident wave. Beyond the two first-order waves occur second-, third- and higher-order waves.



MODULATED FRINGES are produced by the interference of a plane wave and an irregular wave, in this case a cylindrical wave (*left*). Where the angle between the plane and the distorted wave fronts is large the fringe pattern is fine; where the angle is small the fringe pattern is coarse. When illuminated with a beam of coherent light, the modulated fringe pattern acts like an imperfect diffraction grating, producing diffracted waves that are distorted (*right*). The diverging first-order diffracted wave is responsible for the virtual image of the original object; the converging first-order diffracted wave is responsible for the real image of the object.

reconstructed waves will be diffracted in different directions and the reconstructed images will form in different locations.

Wave-front reconstruction photography, although appearing to offer exciting possibilities, has in the past been confined to the laboratory and for some time at least will remain so. The major reason for this is the strict coherence requirements for the light source used in the process. Ordinary light lacks this coherence property, and sources of coherent light are comparatively expensive and inconvenient to use.

There are two kinds of coherence—temporal and spatial—both of which are required for wave-front reconstruction photography. Temporal coherence, or monochromaticity, is required because the fringe pattern generated by the interference process is a function of the wavelength of the illumination. If the spectrum of the light is broad, each wavelength component produces its own separate pattern, and the resultant of all the wavelength components acting at once is to average out the fringes to a smooth distribution. A limited number of spectral components can be superimposed, however, as when three monochromatic waves, comprising the three primary colors, are used to achieve wave-front reconstruction imaging in color. The relaxation of the monochromaticity requirement cannot be carried very far, and each of the three color components must cover a quite narrow spectral band.

The other coherence requirement—spatial coherence—means that the light has been derived from a point source or that the light is capable of being imaged to a small spot or point. If the source lacks spatial coherence (that is, if it is broad), then each element of the source produces interference fringes that are displaced from those of other elements; the sum of many such sets of fringes averages to some very nearly uniform value, and the fringe pattern is absent.

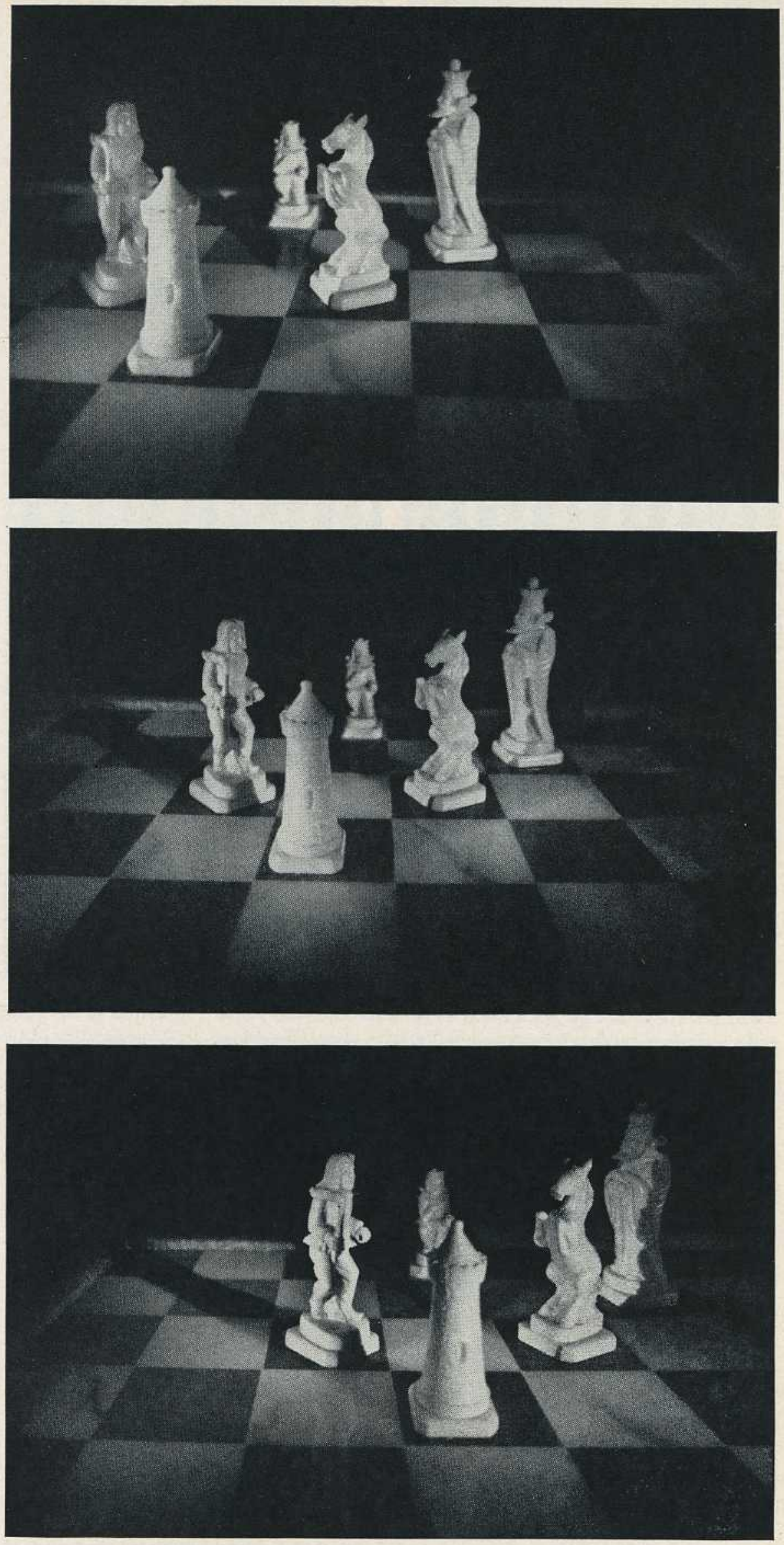
It is possible to meet both coherence requirements using traditional sources, such as a mercury-arc lamp. Monochromaticity is obtained by passing the light through an optical device, such as a monochromator or a narrow-band color filter. This process discards all spectral components except those in a narrow band. Spatial coherence is obtained by focusing the light onto a pinhole. Since only a small fraction of the total light output of the lamp can be focused onto the pinhole, the traditional source is quite inefficient, and only an extremely small fraction of the total light emission is available for illumination of the object.

The light produced by a laser, on the other hand, is highly monochromatic and has extraordinary spatial coherence, thus making the wasteful processes described above unnecessary. The available light is several orders of magnitude greater than the monochromatic, spatially coherent light available from other sources. Hence the laser is greatly superior to all other known sources for wave-front reconstruction photography and is certainly in large part responsible for the interesting results that have already been achieved.

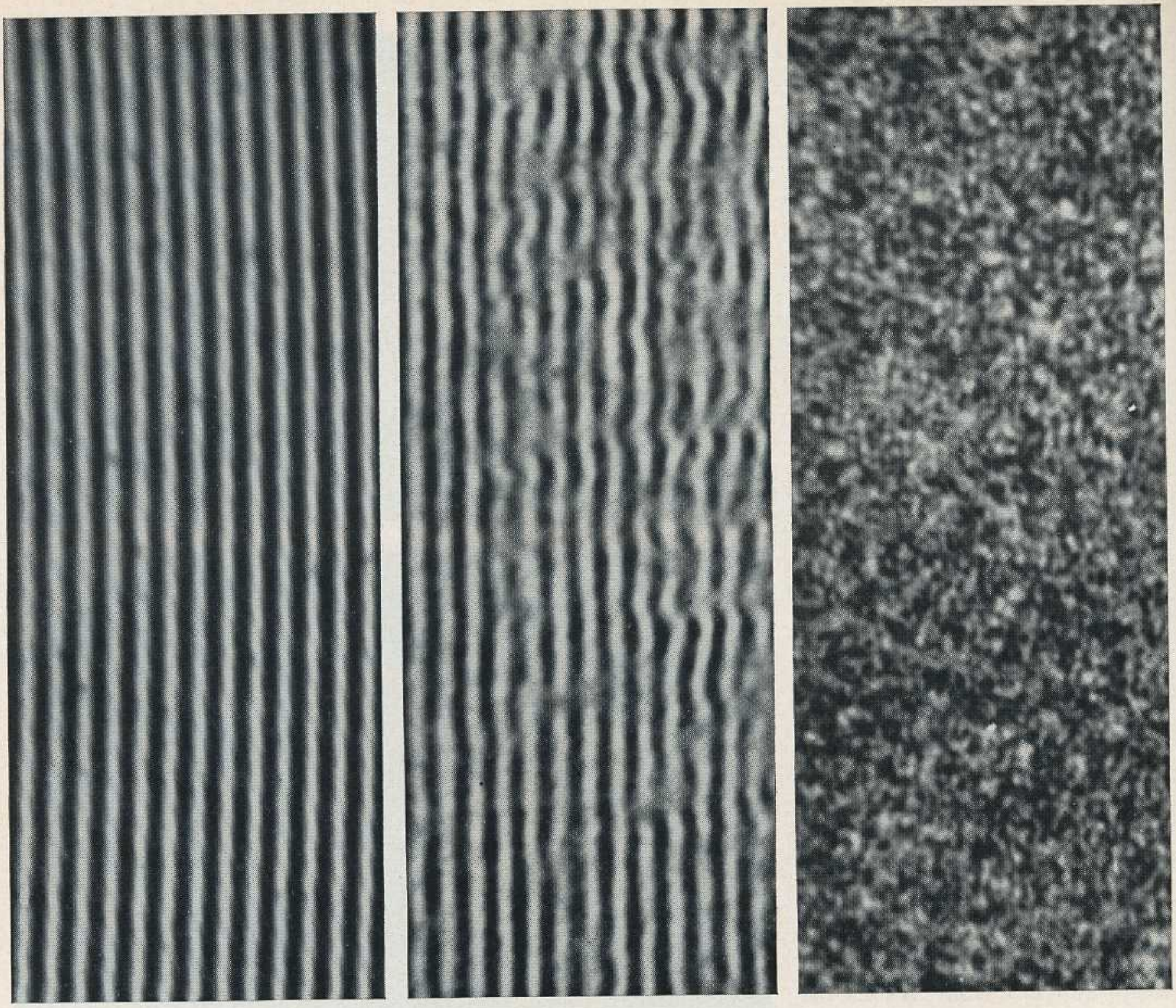
With a high-quality technique for producing fascinating and unusual images fully demonstrated, questions naturally arise as to what applications are to be found for it. Since its discovery by Gabor, many uses for the wave-front reconstruction process have been suggested, and more recently the number of proposed applications has grown rapidly.

Two applications that come to mind immediately are in television and motion pictures. It is possible in principle to produce a hologram television system, since a hologram can be recorded on the photosensitive surface of a television camera just as readily as on a photographic emulsion. Moreover, the hologram data can be transmitted and reconstructed in a receiver. Such a system would produce virtually the ultimate realism.

When the required system and component specifications are examined, however, it is found that they greatly exceed the present state of the art. Transmission bandwidths exceeding present television bandwidths by factors of several hundred are required, unless design compromises are made that result in a partial loss of the dramatic results attainable from holograms. Cam-



PARALLAX EFFECT is evident in these three virtual-image photographs, all made from the same hologram. The apparent displacement of the chessmen resulted from moving the hologram slightly. The same effect could have been obtained by keeping the hologram stationary and moving the camera or by keeping both stationary and moving the laser.



THREE INTERFERENCE PATTERNS show the effects of amplitude and phase modulation of a spatial carrier wave. The fringe pattern at left was formed by two plane waves impinging on a photographic plate at a slight angle to each other. One of the waves responsible for the pattern at center has been modulated to a small degree, producing slight variations in fringe contrast and irregularities in the shape of the fringe contours; the pattern is an enlarged section of a hologram of a comparatively simple photographic transparency. The interference pattern at right is an enlargement of section of a hologram of a diffusely reflecting, three-dimensional object. The degree of modulation is so great that the interference fringes have lost continuity and are no longer identifiable as fringes.

eras, picture tubes and associated components must also be much better than present-day equipment. In addition, the objects would have to be illuminated by laser light, and the receiver similarly would have to contain a laser; present lasers are inadequate for these tasks and would require improvement. The potential is great but the price is still quite high. Methods are being sought for reducing the stringent requirements on system bandwidths, with some initial success, but much remains to be done. For hologram motion pictures the problems are similar and even more severe.

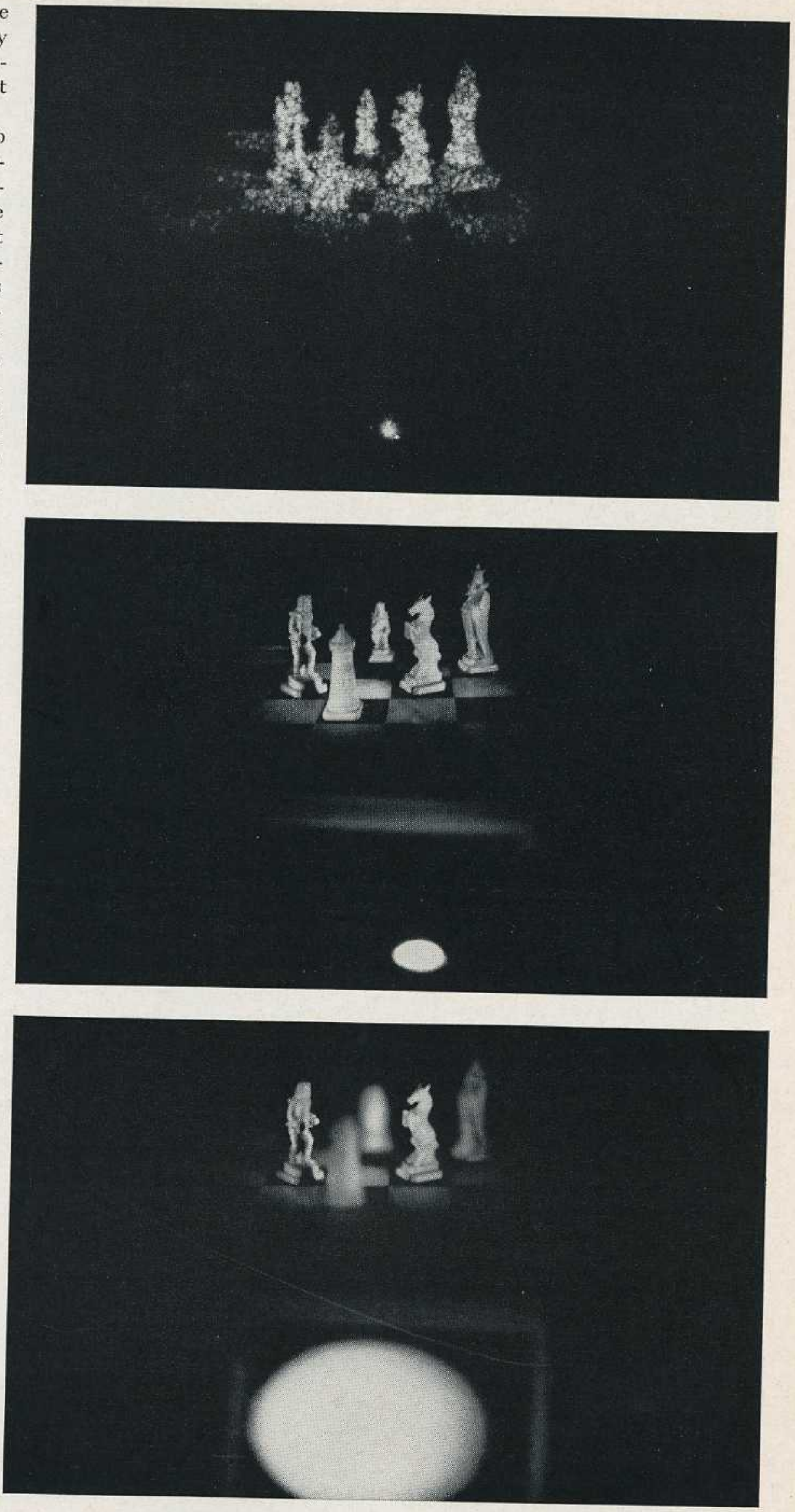
As laser sources improve, wave-front reconstruction photography may emerge from the laboratory and become, through its remarkable three-dimensional imaging properties, an important photographic method for simulation and training devices and for applications in which a highly exact reproduction of the object is required.

Historically microscopy has been the primary area of application for the wave-front reconstruction method; Gabor's original applications were in this area. By the use of divergent beams of radiation Gabor, as well as El-Sum and Albert V. Baez at Stanford, have demonstrated that great magnification can be achieved with wave-front reconstruction, entirely without the use of lenses. Moreover, the hologram can be made with radiation of one wavelength and the reconstruction with another. Gabor proposed to produce a hologram with electron waves in an electron microscope and to make the reconstruction using visible light. By this means the highly developed methods of optical imagery can be applied to image formation in the domain of electron waves, where lens technique is less perfectly developed. Similarly, El-Sum and Baez have made holograms with an X-ray microscope and the reconstructions in visible light. This application holds much promise, because X rays can be focused only crudely and with extreme difficulty. The resolution achieved in X-ray microscopy falls several orders of magnitude short of what is theoretically possible, a condition that can be remedied by wave-front reconstruction methods. Technical difficulties have hampered progress in this area, but the difficulties—primarily the lack of X-ray sources of suitable intensity, monochromaticity and spatial coherence—do not appear insurmountable.

In an application developed by two of the authors' colleagues, Robert Powell and Karl Stetson, the vibratory motion of a complicated object can be measured with ease by the wave-front reconstruction method. The light reflected from such a vibrating object loses its coherence in a predictable manner. Consequently the image reconstructed from a hologram has superimposed on it a contour pattern of the vibrational amplitude; from this reconstruction the amplitude of vibration for each point on the object can be obtained at once by simple inspection of the hologram image.

Brian Thompson, George Parrent and their co-workers at Technical Operations, Inc., have developed an application that has a remarkable simplicity. They were faced with the problem of measuring the distribution by size and other properties of floating, foglike particles in a sample volume. Such particles generally do not remain stationary long enough for the observer to focus on them. In addition, it is often desirable to photograph all the particles in the volume at a given time. The wave-front reconstruction method offers an ideal solution to the problem. A hologram is made by illuminating the volume with a pulsed laser and photographically recording the transmitted light. A short-pulse laser is used to "freeze" the motion of the particles. In the reconstruction an image of the entire volume is produced, and the particle size, distribution and cross-sectional geometry can be measured by microscopic examination. (Although Thompson and Parrent have exploited both the three-dimensional imaging capabilities of the hologram process and the extraordinary coherence properties of the laser, their efforts are unrelated to ours and have developed the original ideas of Gabor along quite different lines.)

Additional applications should develop in time, particularly as advancing technology provides new devices that can facilitate the wave-front reconstruction method. In particular, high-power pulsed lasers with excellent coherence properties should bring about significant advances. It seems safe to predict that most future applications will center on the three-dimensional, highly realistic imagery that the method produces and that is unmatched in this respect by other photographic methods.



ENTIRE IMAGE of the original scene is reproduced by any part of the hologram, however small. At top the unbroadened laser beam, about a half-millimeter in diameter, is directed at the hologram (*faint rectangle in foreground of each photograph*). Since photographic resolution is a function of the aperture of the imaging system, the image appears blotchy and ill-defined at this aperture. As successively larger parts of the hologram are illuminated (*middle and bottom*) resolution is improved, but the depth of field of the image decreases.