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Modern Aspects of Holography

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MODERN ASPECTS OF HOLOGRAPHY

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1. INTRODUCTION:

While discussing holography, it is customary to begin with a comparison of photography with holography. Both attempt to record and restore object scenes generally involving light and a physical medium. In photography an image of an object is projected onto a light sensitive medium and the medium thus stores the brightness or irradiance distribution in the object scene. A photograph is a 2-D record of a 3-D scene. Since the recording medium is insensitive to phase variations while the scene to be recorded has both an amplitude and a phase structure, photographic record is an incomplete record.

It is evident that both amplitude and phase must be stored, if the wave field (object) is to be wholly recorded. In photography the limitation is due to the recording process. It goes to the genius of Denis Gabor who suggested the method of holography as a means to record and restore complete wave field. The inability to record phase variations by a recording medium was overcome by the addition of a background or reference light to the object light, thereby converting phase differences into intensity variations. The physical medium can now readily respond to this coded (interference) pattern. The resulting record was named 'a hologram' by Gabor. The two step process of recording the interference pattern due to an object and reference wave and retrieving an image of the object from the hologram by illuminating the hologram with the reference light is termed holography. Thus was born an exciting new subject in 1948.

The history of holography can be considered to have gone through three cycles. The first cycle had its origin in 1948 when Gabor's paper appeared in Nature [1]. Innovative though it was there was not much of excitement nor any widespread activity in the period following the initial work. The laser was yet to arrive on the scene and other practical difficulties such as the presence of twin images in Gabor's method were to be overcome. The second cycle began in the mid '60s with the paper by Leith and Upatnieks [2] involving the use of a CW laser and an off-axis technique. In the period which followed, there was not only excitement but even over-enthusiasm as it was felt that holography can offer the magic solution to many a scientific and technological problems. In reality it turned out to be falling short of expectations. The difference is essentially due to the time period needed to translate a scientific concept into a mature practical technology. However this is the period in which several in-depth studies on the requirements, properties and limitations of holograms and holography were carried out. To that extent, this has been the most crucial period. The third and the "modern" cycle can be considered to have begun in the mid '70s. This period is dominated by a number of "applications of holography" and the enthusiasm for the subject is tempered by realism. A recent special issue [3], a Handbook edited by Caulfield [4], a book by Hariharan [5] and Conference publications [6,7] can be referred to for the modern developments in holography. In section 2, the basic theory of holography is given and in section 3, experimental aspects are summarised. Section 4 is devoted to the modern aspects and applications of holography.

2. BASIC THEORY:

Holography is basically a two-step process. In the first step an interferogram of an object wave and a reference wave is made. This can be described by the basic interference equation given below:
object wave:

$$\xi_o(x,y) = a_o(x,y)e^{-i\phi_o(x,y)}$$

Reference wave:

$$\xi_r(x,y) = a_r(x,y)e^{-i\phi_r(x,y)}$$

When these two are brought together in the plane of a recording medium, there results an intensity pattern which is given by

$$\begin{aligned} I(x,y) &= |\xi_o(x,y)+\xi(x,y)|^2 \\ &= |\xi_o|^2+|\xi_r|^2+\xi_o\xi_r^*+\xi_o^*\xi_r \\ &= a_o^2+a_r^2+a_oa_re^{-i(\phi_o-\phi_r)}+a_oa_re^{+i(\phi_o-\phi_r)} \quad \ldots(1) \\ &= I_o^2+I_r^2+2a_oa_r\cos(\phi_o-\phi_r) \quad \ldots(2) \end{aligned}$$

A hologram of the object is obtained by exposing I(x,y) suitably onto a recording medium. While so recording if care is taken to preserve a linear relationship between I(x,y) and the amplitude transmittance of the (photographic) record, we get,

$$t(x,y)=b\cdot I(x,y) \qquad \ldots (3)$$

b is a proportionality constant.

Finally, an image of the object is obtained by illuminating the record made as above, called the hologram, with a replica of the reference light. Thus, the reconstructed wave can be written as

$$\begin{aligned}\xi_{rc}&=\xi_r t(x,y)\\ &=b[a_r e^{-j\phi_r}(I_o^2+I_r^2)+a_r^2 a_o e^{-j\phi_o}+a_r^2 a_o e^{-j(2\phi_r-\phi_o)}]\end{aligned} \qquad \ldots (4)$$

The object wave of interest appears in the second and third terms on the right hand side in expression 4. They are conjugate of each other and also are off-set from each other. It may be noted that the reconstruction is 'whole' since both the amplitude and the phase terms of the object wave are replicated The wavefront that is reconstructed in the same form as the original object wave is called a primary image. It is usually a virtual image. It is formed on the same side as the illuminating light with respect to the hologram. This image is to be seen through the hologram as if looking through a window. The conjugate image on the other hand is usually a real image and can be brought to focus on the other side of the hologram onto a screen. Thus of the two images if one is converging and the other is diverging. It is the virtual image that gives a true 3-D effect complete with depth and parallax.

3. SYSTEM AND EXPERIMENTAL REQUIREMENTS:

A typical arrangement for making holograms of diffusely reflecting objects can be as shown in fig.1. Light from a coherent source (say a He-Ne laser) is split into parts one for illuminating an object and the other serving as a reference beam. Spatial filters in each of the above two parts are used to obtain clean wavefronts before they strike the object and hologram plane. Similarly beam reflectors(mirrors) are used to align the reference and object beams suitably with respect to the hologram axis.

In the hologram plane a holder is located onto which the recording medium (photographic plate) can be loaded. A shutter in front of the laser can serve to control the exposure time. The entire optical arrangement is mounted on a vibration isolation table to ensure stable recording of the complex interferogram due to the interference of the object and reference beams in the recording plane. A few more recording and reconstruction schemes are also included in fig.1.

A highly coherent source is desirable but is not a must. Actually Gabor used mercury light in his first experiments on holography. However, a laser can ease practical difficulties in terms of matching path lengths , exposure time, size of the object etc. Whether the laser should be CW or pulsed will depend on the type and nature of object scene and the severity of the environmental conditions.Stationary objects can be readily handled with CW lasers while humans and other moving objects as also transient events can be recorded only with pulsed lasers. With high power pulsed lasers the exposure times can be so small that a vibration isolation table for the optical layout is quite unnecessary. The recording medium is usually the photographic emulsion. It has certain limitations in terms of need for a (wet) chemical processing, time lag and non-cyclic usage. Hence, other types of recorders such as thermoplastics, photoresists, photo-refractive crystals etc. have been investigated. Finally, display holograms are unique in that they need to be large in size, multiplexed, multicolored and while reconstructing the illumination preferably be done with white light.

3.1 Holograms - types and properties

Holograms are of many types and their properties vary depending on the type. Some of the factors upon which classification of holograms is based are the types of recording media (eg., thin, thick), type of modulation produced upon reconstruction (eg., phase only, amplitude only), recording geometry or configuration (eg., Fresnel, Fraunhofer), the nature of light (eg., coherent, incoherent), the type of radiation (eg., microwave, acoustical), and related techniques (eg., computer generated, scanned). A summary of some of the important types of holograms and their features are given in Table 1. For more details, please refer to Chapter 3 by Cathey in [4].

Table I : Classification of Holograms

S.No	Type of Hologram	Features/Description
1a	Fresnel hologram	Object is close to the hologram;sometime a lens is used to project an image onto the hologram (image plane)
1b	Fraunhofer hologram	Object is far enough or small in size so that the hologram is in the far field of the object.
1c	Fourier transform hologram	A point reference source is used; A lens Fourier transforms a point source as also the object distribution; a special case of this is the lensless Fourier transform.

2a	Extended reference hologram	These are special holograms wherein the size and nature of the reference beam is unique.
2b	Local reference hologram	The reference wave originates from the object wave. Source coherence and object distance can be related
2c	Speckle reference hologram	A focused spot on the object provides a speckle reference; cab be used to compensate for phase distortions of the medium.
3a	Incoherent hologram	Usually the temporal coherence of the source used is poor
3b	White light hologram	Recording with coherent light but readout with white light; colour holograms, rainbow hologram etc are the variants of this
3c	Multiple exposure holograms	Incoherent superposition of several holograms on the same emulsion but recorded with coherent light
4a	Phase only hologram	Only phase information is preserved; computer generated hologram, kinoform are other variants of this type
4b	Amplitude only hologram	Similar to above but amplitude only is preserved
4c	Thin hologram	Recording/storage occurs at or near the surface of the medium. Reconstruction efficiency is low
4d	Thick hologram	Volume recording as against recording in a plane; high efficiency and wavelength selective
4e	Reflection or transmission hologram	Reconstruction light either bounces off or passes through the medium

3.2 Hologram recording media:

It has been realised early in the history of holography that the future of holography is very much dependent on the availability of optimum recording materials. Fortunately, apart from the commonly used photographic emulsion, a variety of other media have been developed and exploited. Much of the progress in commercial applications of holography such as display holograms can be attributed to the advances in recording media and techniques. Table 2 gives a summary of the different recording media and their properties. For more details a review by Gladden and Leighty may be referred, Chap.8.3 in [4].

Table 2 : Recording Media

class of material	Examples	Method of preparation	recording process	properties
Photographic	Kodak 649F Agfa 8E70, 10E70 etc	coating on acetate or glass base	Wet chemical processing; reduction to Ag-metal grains; bleaching for phase holograms	non-cyclic use, good sensitivity and resolution
Dichromated gelatin		coated film or converted from photoemulsion	wet chemical;photo cross linking;thickness/index change; phase type	Permanent record, low speed
Photo resists and photo polymers	Shipley AZ1350 Kodak KPR PMMA	coating or casting of films	Photo polymerization, formation of organic acid; index change or surface relief	permanent record, sensitivity to uv/blue light, volume recording

Thermoplastic/ photoplastics		Evaporation and coating	Formation of a electrostatic latent image	index change or surface relief, reusable, low speed but high resolution
Photochromics	CaF_2:La $LiNbO_3$:Fe	crystal wafers	ionic and electron traps, photo induced effects (index changes)	cyclic use, poor storage life, modest resolution, volume holograms

There are also a number of other recording materials such as electrooptic and nonlinear optic materials, amorphous semiconductors, magnetic films, colour centers in alkali halides and others [8].

4. MODERN ASPECTS AND APPLICATIONS:

Developments in holography can be chronologically outlined as follows:

1948-51: Gabor's invention of holography; emphasis on microscopy; recording at short wavelength (electron beam) and reconstruction at long wavelength (optical); similarity to Bragg diffraction process in x-ray crystallography; appropriate for imaging transparencies; useful with conventional (non laser) source; reference and object beams in-line; two images - one focused and the other unfocused - appear in the fields of view.

1960-64: Arrival of the laser; laser holography and off-axis (carrier frequency) technique invented by Leith and Upatnieks; recording at long wavelength (microwave) and reconstruction in optical region (synthetic aperture radar imagery); source coherence and high resolution of recording media are important; diffusely reflecting 3D objects (as opposed to just transparencies) are readily imaged.

1962-65: Denisuk's work on (Lippmann) holography; colour-volume-white light holographic techniques and a basis for breath-taking displays.

1964-70: Complex spatial filters (Vander Lugt type) for data processing; Powell and Stetson introduce hologram interferometry;acoustical holography; Benton's rainbow hologram; holographic memories; Computer generated hologram (Lohmann); multiplexed hologram; holographic optical elements (HOE) and many other techniques and developments.

Beyond 1970: Consolidation of the results of earlier inventions and expansion of application areas. These include display and pictorial holography [9], holographic optical elements [10], holographic optical interconnects [11], holography for biology and medicine (and microscopy) [12], holographic memory and optical neural computing [13], holographic nondestructive testing [14] and many other areas. Some of these developments and applications are highlighted in what follows.

COMPUTER GENERATION

In Computer generated holography (CGH) the amplitude and phase of a defined object is represented by a size and position varying aperture and the hologram is made using suitable photography of the pattern generated as above. In Lohmann's original method the actual CGH consisted of many apertures of various sizes shifted in positions relative to a standard array position in a defined cell. The size of the aperture decides the amplitude and the relative position the phase, for a given cell. The phase only CGH method of making a hologram is called a kinoform. Recent advances and applications of CGH have been discussed by Lee [ ]. CGH based spatial filters for recognition of patterns - deterministic as well as statistical, testing aspheric surfaces, transforming of wavefronts (eg., donut-shaped to Gaussian beams) and realization of multifunction optical elements are some of the applications of computer generated holography. This technique does not require a physical object and hence is more versatile.

OPTICAL ELEMENTS

Holographic optical elements (HOE) are based on the unique imaging properties of holograms. Holo elements are often constructed by recording the interference pattern between a plane wave and a spherical wave or between two spherical or two plane waves. For example, a hologram made by the superposition of a plane and a spherical wave can act like a lens ie., can converge a collimated beam to a point at a distance of a focal length. HOEs are wavelength sensitive and can be used only in a narrow band region. Conventional optical elements made of glass or plastics can be used over a broader wavelength band than HOE. Also, in conventional optics, refraction and reflection play the major role while in HOE, diffraction plays the major role. Aberration is a common cause of performance deterioration in both conventional and holographic elements. Careful design and control of recording parameters (geometry, wavelength, exposure, processing etc) are therefore important to achieve quality HOE. Diffraction efficiency and signal-to-noise ratio are two of the practical parameters to express the performance of HOE. A recent state-of-art review by Pappu [16] can be referred for a detailed understanding of HOEs and their applications. Beam combining, laser scanning, spectral filtering, optical processing and computing, head-up display, optical waveguide elements for communication and many other areas are likely to benefit from the availability of high quality

HOE. Holographically generated gratings in optical fibers have been demonstrated by Hill et al [17] and Morey et al [18] and these can lead to compact distributed sensors and a host of communication and signal processing applications. HOE for synthetic aperture radar data processing is also known [19].

DISPLAY

Among the many virtues of holography its ability to record and display 3D images is outstanding. Recent developments in this field include fixed multicolor images viewable with white light, mass-produced embossed holograms with changing colours and possibility of 3D motion picture and TV for mass-audience. Jeong [20] can be referred for a simple but effective overview of this topic. Rainbow hologram is a transmission hologram with a narrow bandwidth and is well suited for mass production by embossing. Synthetic holograms are made by a sequence of strip-holograms and is suited for portraitures. 360° viewable cylindrical holograms are made by surrounding the object with a circular piece of film. These and allied techniques promise an exciting future in display and viewing areas.

NON-DESTRUCTIVE TESTING

Holographic nondestructive testing (HNDT) has been one of the most fruitful applications of holography. Hologram interferometry is the specific form of practical HNDT. All of the classical interferometric test methods have been realised in Holo-interferometry with added advantages such as objects of any shape, size and finish can be used with HNDT. Real Time, Double exposure and Time Average are the techniques employed to study stress, fatigue, vibration, fluid flow and many other phenomena. Diode laser [21], fiberoptic [22] and phase stepping interferometry [23] are some of the modern additions to HNDT. Visualization of leakage flow in buildings [24], a spectroscopic method for analyzing modes and amplitudes of randomly excited objects [25] and a speckle holography method of measuring small displacements [26] have also been reported.

ABERRATION CORRECTION

Image formation - by holography as well as by other means - is affected by the presence of an inhomogeneous medium in the intervening space. If the medium is stationary then it is considered to be an aberration producer. Many aberration reduction techniques have been developed based on holographic methods [27]. Recently a new technique for correcting errors due to abberations in a telescope has been reported [28]. A dynamic holographic method of imaging phase objects using a volume hologram in a single crustal and incomplete aberration removal has been described by Brody and Leavitt [29].

OPTICAL INTERCONNECTIONS

Optical interconnects between VLSI circuits, computing chips or boards are important in optical computing. Thus high speed communication and high speed computing call for effective optical interconnection schemes. Optical fibers, integrated optic waveguides and free space interconnections are all studied for this purpose and holographic techniques using photorefractive materials promise reconfigurable massive interconnections. These and related matters are discussed in recent papers by Chiou and Yeh and others in a special issue of Applied Optics [30]. A related development is optical associative memory which is especially important in neural computing. Associative holographic memory using phase conjugate mirrors has been reported by Soffer et al [31]. Paek et al [32] have described an ultrafast holographic memory using surface emitting microlaser diode array (SELDA). SELDA has certain unique features such as low threshold current (~1 mA), high device density (a million lasers on a 1 cm^2 chip), narrow line width (~0.1 nm) and a high switching speed (~1 ns).

CONCLUSION: The physics and technology of holography and its applications have come a long way since its invention. The literature is rich with new ideas, techniques and innovative uses of holography. It is a rewarding experience for a modern researcher to go through the theory and practice of holography. We conclude this review with a graphic display of the science of holography in fig.2. A tall and broad holographic tree with many branches has grown from the collective scientific effort of the researchers the world over, fed by streams of coherent sources and nutrients in the form of recording media. Many and varied are the fruits of this tree - head-up displays, compact disc, unique optical elements, display of non-existent object are a few to mention - and one is certain to reap still higher yields in the years to come.

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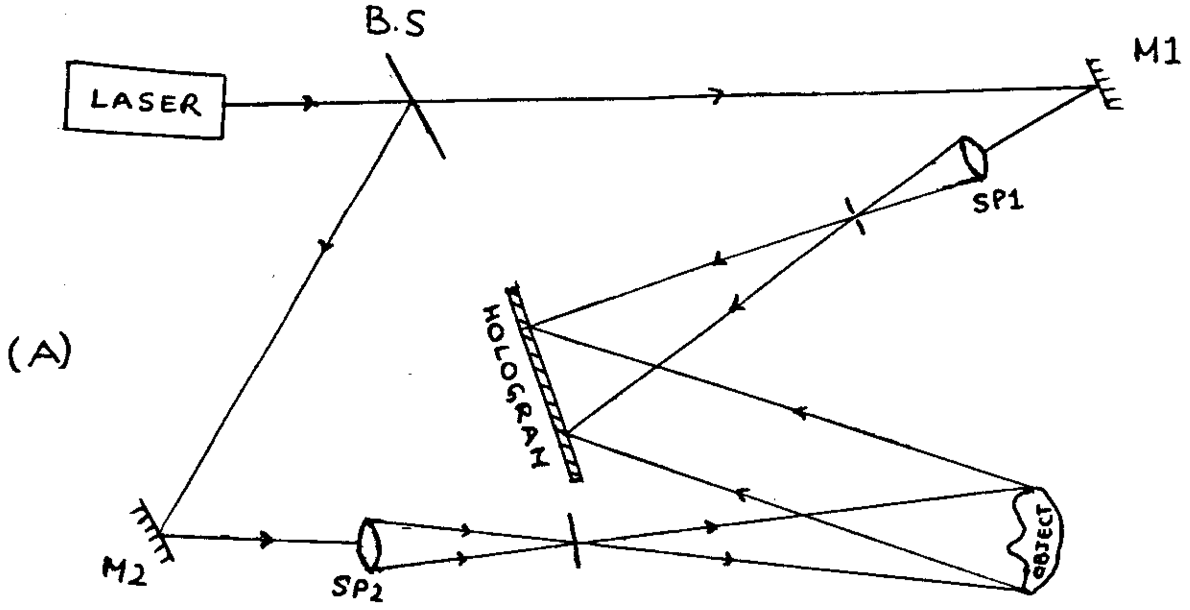


B.S. → BEAM SPLITTER

M1, M2 → MIRRORS

SP1, SP2 → SPATIAL FILTERS

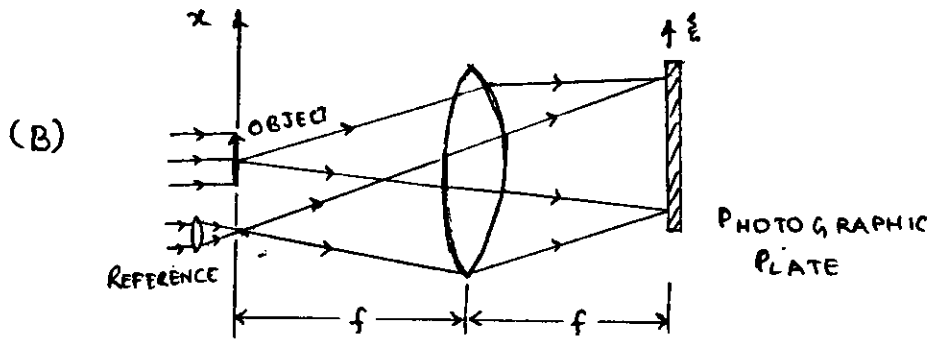
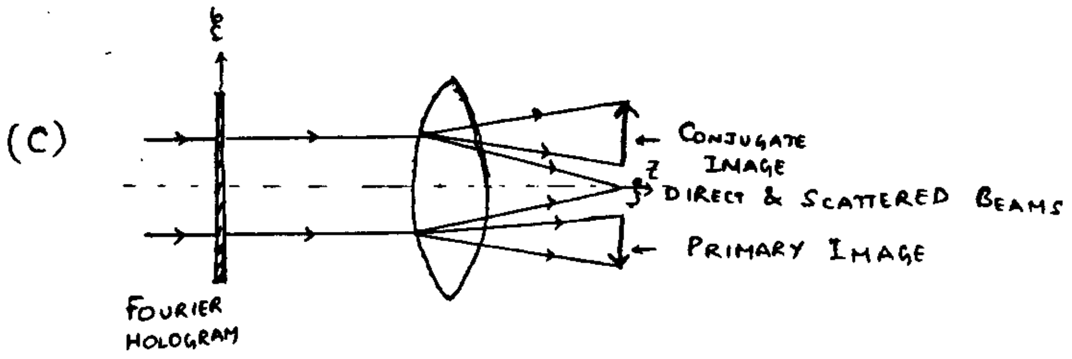


Fig 1

(A) OFF-AXIS RECORDING

(B) FOURIER TRANSFORM RECORDING.

(C) FOURIER TRANSFORM RECONSTRUCTION.



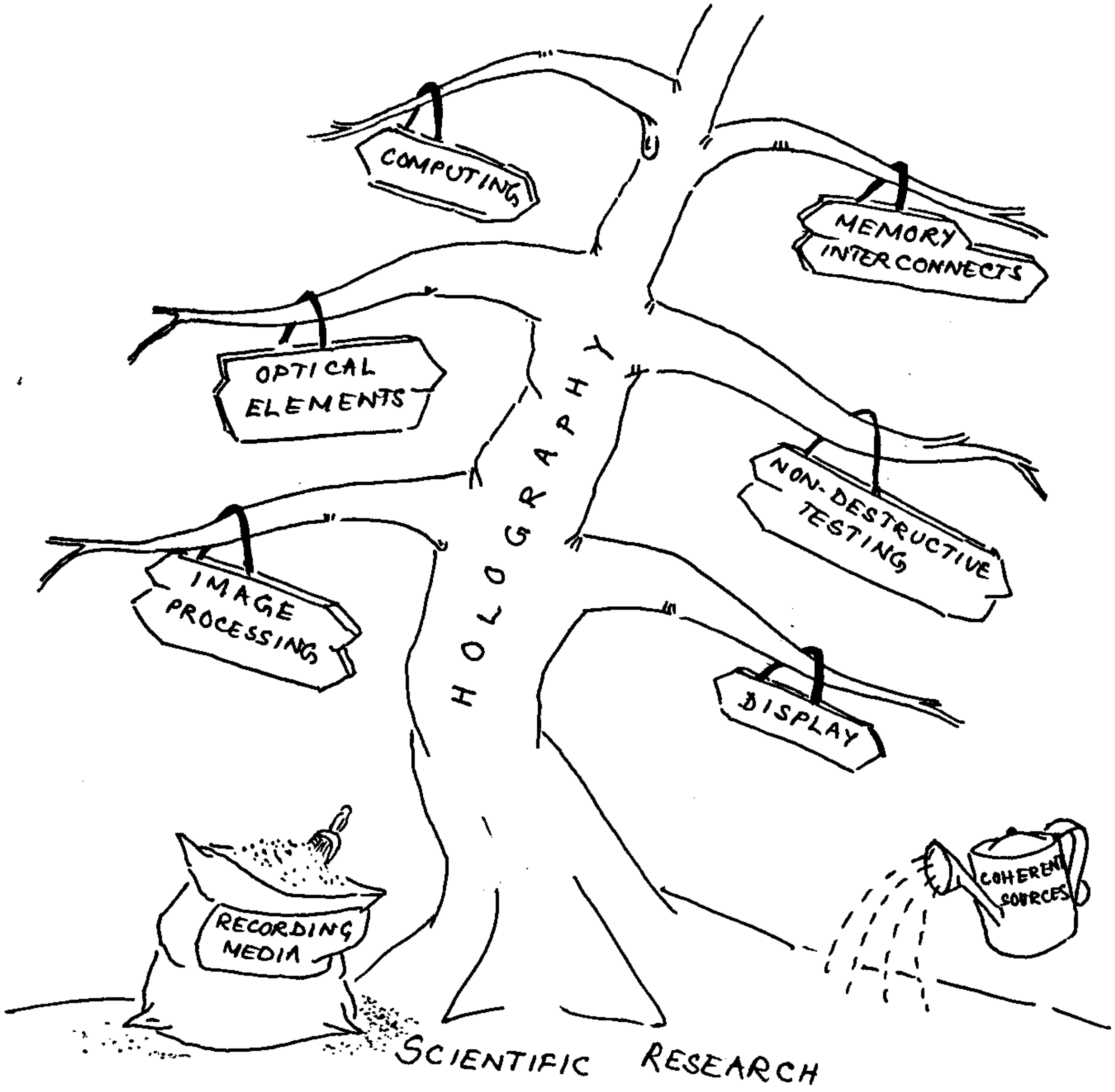


FIG. 2 : THE HOLOGRAPHIC TREE