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Physics in Perspective

# Absorbing New Subjects: Holography as an Analog of Photography

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I discuss the early history of holography and explore how perceptions, applications, and forecasts of the subject were shaped by prior experience. I focus on the work of Dennis Gabor (1900–1979) in England, Yury N. Denisyuk (b. 1924) in the Soviet Union, and Emmett N. Leith (1927–2005) and Juris Upatnieks (b. 1936) in the United States. I show that the evolution of holography was simultaneously promoted and constrained by its identification as an analog of photography, an association that influenced its assessment by successive audiences of practitioners, entrepreneurs, and consumers. One consequence is that holography can be seen as an example of a modern technical subject that has been shaped by cultural influences more powerfully than generally appreciated. Conversely, the understanding of this new science and technology in terms of an older one helps to explain why the cultural effects of holography have been more muted than anticipated by forecasters between the 1960s and 1990s.

*Key words:* Dennis Gabor; Yury N. Denisyuk; Gabriel Lippmann; Emmett N. Leith; Juris Upatnieks; holography; photography; stereoscopy; art; wavefront reconstruction.

## Introduction

The emergence of new subjects in science and technology is seldom a neutral process in society. Historians have long recognized that science, technology, and culture are interlinked, but generalizations about their relationships have tended to remain contentious because the strength and direction of their mutual influences have been disputed case by case. While some work in the history of science has focused on the evolution of new subjects, relatively few studies have explored directly how this process is influenced by preexisting technologies.[1]

I discuss the history of holography and photography to explore how perceptions, applications, and forecasts of new subjects can be shaped strongly by prior experience. I argue that the evolution of holography was simultaneously promoted and constrained by its identification as an analog of photography, and that this association influenced its assessment by successive audiences of practitioners, entrepreneurs, and consumers. One consequence is that holography can be seen as an example of a modern technical subject that has been shaped by cultural influences more powerfully than generally appreciated. Conversely, this understanding of this new science and technology in

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terms of an older one helps to explain why the cultural effects of holography have been more muted than anticipated by forecasters between the 1960s and 1990s. Holography illustrates how cultural predilections can transform a radically new concept into a more easily absorbed form.

## Dennis Gabor and the Context of Microscopy

The term "holography" became dominant by about 1966 to describe techniques and concepts that had been circulating for nearly two decades among a handful of researchers. The first of these investigators, and the sole winner of the Nobel Prize in Physics for 1971 "for his invention and development of the holographic method," was Dennis Gabor (1900–1979, figure 1), an émigré Hungarian electrical engineer and physicist employed at the British Thomson-Houston Company in Rugby, England, who introduced the concept of "wavefront reconstruction" in 1947. Attempting to improve the quality of imaging by electron microscopes, Gabor conceived a two-stage hybrid technique. First, the electron beam of the microscope would be employed to cast a shadow of a microscopic object and to record it on photographic film. Owing to the wave nature of electrons, this so-called "physical shadow" would be ringed by interference fringes caused by the interference of portions of the wavefront after diffraction by the object. Second, this photographic recording, which Gabor dubbed a "hologram," would be used to reconstruct a magnified image of the object: the tiny film record would be illuminated by a beam of coherent light that then would be diffracted by the recorded fringes to recreate a visible image.* The magnification of this image would be proportional to the ratio of the wavelengths of the electron beam to that of visible light, or by a factor of about 10,000. Gabor was not interested directly in the magnification process, because contemporary electron microscopes were capable of achieving such magnifications, but he hoped that the technique could improve spatial resolution. Electron microscopes had been constrained by the unavoidable spherical aberrations of their magnetic lenses to a spatial resolution of about 10 nanometers. Gabor intended that his two-step process would allow aberration-correcting *optical* lenses to be used in the imaging stage to yield images some ten to one hundred times sharper, or enough to resolve individual atoms.

To Gabor's contemporaries, his novel concept was arcane, complex, and unpromising. Sir Lawrence Bragg (1890–1971), well-known for his early work in X-ray diffraction** and now Gabor's informal mentor, wrote to him on July 5, 1948, that "I think I am beginning to understand the principle, though it is still rather a miracle to me that it should work."[2] A handful of other physicists who explored wavefront reconstruction criticized Gabor's expository style, unjustifiable optimism, and technical limitations. For

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* The hologram can be understood as a generalized Fresnel zone plate, reconstructing an image by diffracting the wavefront into multiple foci, an association that Gabor recognized only three years later.

** William Lawrence Bragg (1890–1971) had worked with his father William Henry Bragg (1862–1942) on the X-ray analysis of crystal structure. They were awarded the Nobel Prize in Physics for 1915 for their work.

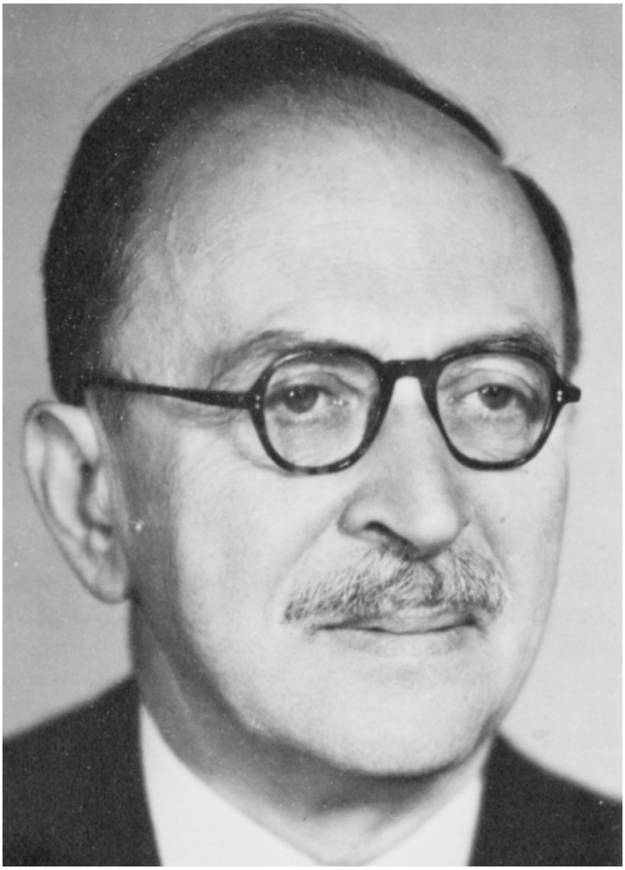

**Fig. 1.** Dennis Gabor (1900–1979) in middle age. *Credit*: Courtesy of the Massachusetts Institute of Technology Museum, Cambridge, Massachusetts.

example, Gordon L. Rogers (b. 1916), Gabor's closest collaborator in the field, reported to a colleague on September 2, 1952, that "by now several people … have taken the snags out of the original draft [of the book chapter Gabor has written], and his claims are now much more modest and reasonable. I still feel, however, that they are not very helpful, though they are no longer unsound."[3] Similarly, Max Born (1882–1970) had written to Gabor on February 21, 1951, that "I have read more of your MS. And I think that your considerations are most ingenious. But I can at the same time not conceal that they always seem to me a little weird, and prickle my physical sensitivities."[4]

Gabor's critics defined the nature, boundaries, and problems of wavefront reconstruction by viewing it as a new form of *microscopy*, an imaging technique applied to microscopic objects. There are at least four explanations for this perceptual pigeon-holing: first, Gabor's conception had begun with the problems he perceived were involved in electron microscopy; second, the hybrid system that he dubbed the "holoscope" had formal similarities to earlier concepts in the design of optical instruments, in particular, the Abbe theory of imaging in microscopes* and Bragg's recent X-ray microscope;[5] third, he had promoted wavefront reconstruction specifically to microscopists in demonstrations and articles; and fourth, those who took an interest in Gabor's work were themselves seeking to improve optical or short-wavelength microscopy. Their perspective on wavefront reconstruction thus was a consequence of their disciplinary commitments and perceptions as microscopists; they viewed wavefront reconstruction with the mindset of microscopists. The content of this new subject was influenced by its past disciplinary context.

A second constraint followed from the implicit assumptions these researchers made about the boundaries of their subject. As Bragg and Born indicated above, the concept and characteristics of wavefront reconstruction were alien to them. One of its miraculous attributes was that this two-stage imaging technique produced a *three-dimensional* image. Gabor's papers and patent emphasized that wavefront reconstruction recorded three dimensions of a sample, yet he never mused about its application to stereoscopic imaging.[6] This was natural considering his categorization of the technique as microscopy. Thus, microscopes had associated traits that may have seemed inescapable: they are optical devices with a single optical axis, and they used an eyepiece to produce an image. These traditional physical assumptions may well have hindered consideration of unfamiliar imaging geometries. An eyepiece, at the very least, foreclosed the possibility of observing an image in parallax. Gabor and other workers in wavefront reconstruction also may have sensed subliminally that the limited coherence length of their light sources confined the observed sample to microscopic dimensions. A stereoscopic image thus was scarcely conceivable to them.

The most important conclusions this band of investigators drew concerned the drawbacks of wavefront construction as based upon criteria defined by microscopy: Most saw wavefront reconstruction as fatally flawed by the so-called "twin-image problem," in which a fuzzy second (conjugate) image seemed doomed to overlap the desired image, rendering this technique unsatisfactory for any practical use. Gabor himself blamed its lack of technical and commercial success mainly on limitations of the electron source and, later, the inadequate optical coherence of the available light sources.** These negative evaluations stemmed from the histories, backgrounds, and working contexts of Gabor and his contemporaries: Their disciplines and intellectual starting points created perceptual barriers that restricted their conception of this new subject. Constrained in this way by the context of microscopy, Gabor, a highly creative

* Ernst Abbe (1840–1905) was first appointed as a lecturer in mathematics, physics, and astronomy at the University of Jena while working part-time for Carl Zeiss (1816–1888), a microscope craftsman. Abbe's development of a theory of spatial filtering led to improvements in Zeiss microscopes. His ideas were extended by the Dutch physicist Frits Zernike (1888–1966) in the 1930s to invent the phase-contrast microscope for which he received the Nobel Prize in Physics for 1953.

** Optical coherence is the ability of a light source to interfere with itself. Most light sources fluctuate with time and direction of the beam, and so have very little temporal and spatial coherence. Gabor used filtered mercury lamps, which have a coherence length of a fraction of a millimeter; helium-neon lasers, which were subsequently developed, had a coherence length of several centimeters or more.

inventor with direct and recent experience in both stereoscopic imaging and information theory, failed to make conceptual connections between these subjects and his work on wavefront reconstruction.* From his perspective and that of others, the concepts entailed in wavefront reconstruction had been thoroughly explored; they scarcely could recognize the barriers imposed by their working cultures, or perceive alternate routes through its intellectual territory. The social and conceptual shaping of their research was largely invisible to its practitioners.

## Yury Denisyuk and the Context of Photography

The influence of historical and cultural context on the evolution of concepts is further highlighted by a second formulation of holography in the late 1950s and early 1960s by Yury N. Denisyuk (b. 1927, figure 2) at the Vavilov State Optical Institute in Leningrad, the Soviet center for optical research and development. Denisyuk was designing optical devices for naval applications in 1958 and decided to pursue questions of generalized imaging for his advanced *Kandidat* degree; he developed this into a new form of imagery over the next three years, for which received his degree.[7]

Denisyuk knew nothing of Gabor's research when be began his own; instead, he recalled that he was inspired by the science-fiction stories of the well-known Leningrad scientist Ivan Antonovich Yefremov (1907–1972). Indeed, two of Yefremov's stories, which he published after the war, are plausible triggers. They provided a potent mixture of scientific idealism, advice to would-be Soviet scientists and, most curiously, a remarkably detailed discussion of unusual optical devices that were central to his plots. In one story, images of dinosaurs and cave dwellers are revealed on the walls of cliffs and caves; in the other one, an alien optical device is discovered that recreates the lifelike image of a face.[8]

From the outset, then, Denisyuk was concerned with the problem of general imaging, not with devising a new variant of microscopy. He began his investigations in 1958, as he recalled, "to develop image display devices which could reproduce an absolute illusion of the presence of the objects displayed."[9] Realistic three-dimensionality was a feature that conventional photography could not produce, but had been a long-time goal of photographers. Denisyuk retraced the steps of the French physicist Gabriel Lippmann (1845–1921), who had proposed innovative forms of three-dimensional and color photography a half-century earlier, for which he received the Nobel Prize in Physics for 1908.[10] Thus, Denisyuk's search for a general imaging technique – one that could reproduce and record the wave field of light in space – was firmly rooted in photography.

Lippmann's color-photography technique involved placing a thick photographic emulsion in contact with a mirror of liquid mercury, so that light focused by a camera

* At the same time that Gabor was developing wavefront reconstruction at British Thomson-Houston, he was investigating stereoscopic cinema; see P.G. Tanner, and T. E. Allibone, "The patent literature of Nobel laureate Dennis Gabor (1900–1979)," *Notes and Records of the Royal Society of London* **51** (1997), 105–120. Gordon L. Rogers, who was an ardent photographer and had conceived schemes for generating stereoscopic X-ray images, also did not connect stereoscopy with wavefront reconstruction.

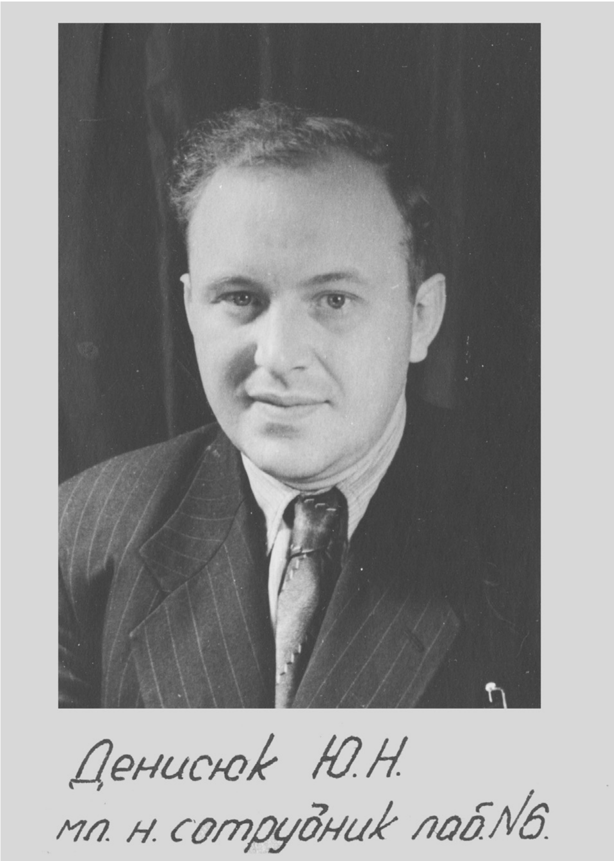


**Fig. 2.** Yury Denisyuk (b. 1927) around 1966. *Credit*: Courtesy of Academician Yu. N. Denisyuk.

lens traveled through the emulsion, was reflected by the mercury mirror, and traveled back through the emulsion, setting up a standing wave in the emulsion for each of the wavelengths of the incident light and thus producing an interference pattern in the emulsion. Recording this interference pattern with monochromatic film, the emulsion simultaneously produced a photographic image – darkening where the light was intense – and acted as a color filter, because each standing wave in the emulsion corresponded to a single wavelength. The result was a full-color rendition of the original image, reflecting the full spectrum of wavelengths in the light source (at least so far as the emulsion was sensitive to those wavelengths).

Denisyuk found that he was able to adapt the practical aspects of Lippmann photography to his new generalized-imaging technique. Thus, he conceived his first experimental objects as a generalized version of Lippmann's liquid-mercury mirror, namely, as a spherical-convex mirror, which would produce a spherical wavefront and standing-wave interference pattern in space. He concluded that his new method would create a structure in a photographic emulsion that would model the surface of a reflecting object.[11] In his paper of 1962, he described the resulting "wave photograph" as "a unique kind of optical equivalent of the object":

> If radiation from the same source that illuminated the object during exposure is allowed to impinge on this structure, it will reflect this radiation in such fashion that the wave field of the reflected radiation will be identical to the wave field of the radiation reflected by the object.[12]

The "wave photograph" thus was a model of the reflecting object. The first images that Denisyuk published were of reflections from convex mirrors and a micrometer scale. In his paper, he summarized his dissertation experiments of the preceding year in which he had used collimated light from a mercury lamp to illuminate both the Lippmann emulsion and these reflecting objects and recorded a standing-wave pattern, resulting in a wave photograph that modeled the spherical mirror. He showed that his unusual photographic plate reflected and focused light, acting therefore more like an optical component than a photographic representation.*

Just as Gabor had gradually extended his understanding of wavefront reconstruction mathematically, so Denisyuk now explained his technique of wave photography mathematically.[13] Conceptually, he moved from something resembling Lippmann's ideas to ones that focused on recording a wave field in space. His ideas were simultaneously constrained and daring: They were constrained by his presuppositions about the suitable optical geometry (Lippmann's work had suggested to him that the reference and object waves should interfere in the photographic emulsion and hence that the technique might be limited to thin reflective objects); they were daring by his envisaging Lippmann's method as a particular case of a more general solution.** Seen in this context, Denisyuk's imaging technique had little in common with Gabor's. Denisyuk's implementation of his technique avoided the experimental problems that Gabor had encountered, but at the same time they revealed a constellation of new ones.

In some respects, Denisyuk's technique was more general than Gabor's. Both had considered interference phenomena and had applied Huygens's principle, but Denisyuk had conceived his studies in terms of recording a spatial relationship – a standing wave in a thick photographic emulsion. He had described this *volume* effect as a phenomenon as yet inadequately named or described, as "the astonishing capacity of the wave fields to depict material objects with a degree of accuracy never attained before."[14] Gabor, by contrast, had conceived a stepwise *process*, in which information was transformed successively from an image to a two-dimensional pattern and back to an image. Denisyuk's method was not encumbered with a "conjugate" image as was

* This nonphotographic property of "holographic optical elements" became a major military application for fighter aircraft displays during the 1970s.

** Denisyuk's envisaging of counter-propagating waves appears entirely logical and inevitable when his goals are considered: He sought to capture the minor deviations from a plane wavefront of light; his emulsion was meant to sample a reflective surface and so was parallel to it. For the same reason, he employed collimated light to obtain a plane wavefront, and shallow objects that would modulate the wavefront by not much more than the emulsion thickness.

Gabor's. However, the light source available to Denisyuk (a high-pressure mercury-arc lamp) had a coherence length of a few tenths of a millimeter, so only very shallow objects could be recorded. Both Denisyuk and Gabor thus recognized that in principle their techniques could provide much more complete information than a photograph, but neither suggested publicly that deep three-dimensional imaging might be feasible.

Denisyuk, like Gabor, found that his research was received poorly by his contemporaries. Despite his acknowledgment of its mathematical similarities to earlier work and his portrayal of his research as an extended, if unintuitive, form of photography, his papers were largely ignored by Soviet scientists as an esoteric and experimentally limited technique. In any event, soon after he finished his dissertation in 1961, he assumed new duties as a laboratory director and was diverted to other work in the Vavilov Institute.

## Emmett Leith and the Context of Synthetic Aperture Radar

Gabor's and Denisyuk's implementations of their concepts, conceived in dissimilar working contexts and cognitive domains, attracted few followers. A third version that evolved toward an overlapping mathematical description but had distinct intellectual origins, however, came to be perceived dramatically differently.

The University of Michigan benefited from targeted-research funding in the postwar period, attracting contracts from the United States military to develop an antiballistic missile as early as 1946, and subsequently battlefield-surveillance systems. Its Willow Run Laboratories (WRL), sited at an airport in Ypsilanti some 15 miles from the Ann Arbor campus, isolated its workers physically and intellectually. They investigated a wide array of technologies, including radar, infrared, acoustical, optical, guidance, and data-processing. They developed an early digital-computer design, the Michigan Digital Automatic Computer (MIDAC), in the early 1950s, and the first ruby maser a few years later.

One of the areas under investigation at Willow Run was the development of a variant of imaging radar that became known as Synthetic Aperture Radar (SAR). A handful of workers understood in the early 1950s that suitable radar data could be processed to yield an image, and they pursued a novel approach that explored the possibility of using optical-processing techniques instead of analog-electrical systems or relatively slow and expensive digital computers. Emmett Leith (1927–2005), a physicist working in an electrical-engineering environment, conceived a relationship between the SAR signal and optical transformations. As he identified successive analogies between communication theory and optics between 1955 and 1958, his ideas evolved towards an understanding of SAR as a two-step imaging process that was formally akin to Gabor's in the very different context of electron microscopy.[15] Leith's conception of optical processing, by contrast, was shaped over a period of years by his working environment amidst electrical engineers.

Leith became aware of Gabor's work by 1956, as did Denisyuk around 1960. Synthetic Aperture Radar had little practical connection with either Gabor's or Denisyuk's work; their different disciplinary contexts shielded their ideas from each other. Their technical jargon and concepts could be translated from one context to another only with difficulty. To use Thomas S. Kuhn's term, the concepts underlying holoscopy, wave photography, and SAR were incommensurable. Kuhn used this term to describe the inability of scientists to comprehend or even discuss concepts developed before and after a scientific revolution,[16] but this also can occur when different interpretations of a phenomenon coexist in different locales. More recently, Peter Galison used an anthropological analogy to describe different subcultures of physics based upon the distinctive instrumentation they employ.[17] He characterized workers trained within these subcultures as belonging to distinct technical tribes speaking different technical languages who communicate by using compromise pidgin dialects in constrained working contexts or trading zones. The situation here is rather different from that concerned by both Kuhn and Galison: Here two disciplines, physical optics and electrical engineering, merged to create a nascent community of workers with a unique perception of a new subject.

Leith's concept was vindicated by the practical implementation of an optical processor for SAR data, which he demonstrated successfully by 1958, and over the next two years he and his colleagues applied the concepts melding communication theory and optics to other kinds of signal processing for their military sponsors.[18] Then Leith and Juris Upatnieks (b. 1936) pursued further research on wavefront reconstruction (figure 3). They applied communication theory to Gabor's concept, developed solutions for the "twin-image" problem, and by 1961 invented high-quality techniques for recording holograms and reconstructing images from them.[19]

Leith's and Upatnieks's research was founded solidly on radar applications and communications theory, but their studies of wavefront reconstruction repeatedly raised questions of imaging. Radar imaging of terrain involved not merely the stark black-and-white transparencies that Gabor had considered, or the specularly reflecting smooth surfaces studied by Denisyuk, but continuous tones diffusely reflected from three-dimensional objects. SAR developments prepared Leith and Upatnieks for the same kind of work in their laboratory. They first investigated the wavefront reconstruction of grayscale transparencies and then diffusely illuminated transparencies and reflective objects. This last stage, and its dramatic results, were made possible by using the newly available helium-neon lasers.

## Leith and Upatnieks and the Analogy to Photography

The Willow Run developments illustrate the influence of working context on the understanding of researchers and in their search for potential applications. Groomed by their research in optical processing, Leith and Upatnieks interpreted their new insights exclusively in those terms. Their imaging research was a sideline of their main classified activity, the improvement of methods to modify and accentuate radar data by optical means. They did not publicize that sponsored-research background, however; instead, they recast their invention publicly as a variant of photography, thus shoehorning it into an existing technological category.

Leith and Upatnieks demonstrated their new imagery to ever-wider audiences after December 1963. Their first demonstrations of grayscale reproductions created a minor flurry of publicity, but their demonstrations of three-dimensional imagery during the

**Fig. 3.** Juris Upatnieks (b. 1936, *left*) and Emmett Leith (1927–2005) in 1963. *Credit*: Courtesy of the Bentley Historical Library, Ann Arbor, Michigan.

first four months of 1964 produced a true explosion of attention. This publicity redefined the content of their new technology. Its origins in Synthetic Aperture Radar were hidden. Instead, their technique was trumpeted in a press release by the American Institute of Physics (AIP) as "lensless photography," which created a new perception of its history, concepts, and future.

The AIP press release reshaped the meaning of Leith's and Upatnieks's accomplishment through its text and illustrations. Its text emphasized that their technique was a sophisticated form of photography. Holograms and photographs, after all, were both recorded on light-sensitive emulsions, and both produced an image when suitably viewed. The AIP announcement translated the unfamiliar components of the concepts of wavefront reconstruction into more conventional ones – a "blurred photographic negative," an "optical system," "projector-like device," "projection screen," and "camera-like device." Further, the accompanying illustrations of the diffraction hologram and of its reconstruction were unfortunately reproduced in the identical size and format, suggesting that one mapped directly onto the other (figure 4). This misidentification was consolidated by the description of the hologram as a "blurred image," while the holograms of grayscale images, in fact, were unrecognizable mottled gray plates that one reporter described as a "buttermilk sky."[20] Even worse, the reconstructed image of a head in the press release was at about the same position as a large interference ring on the hologram, suggesting a direct correspondence of one with the other.

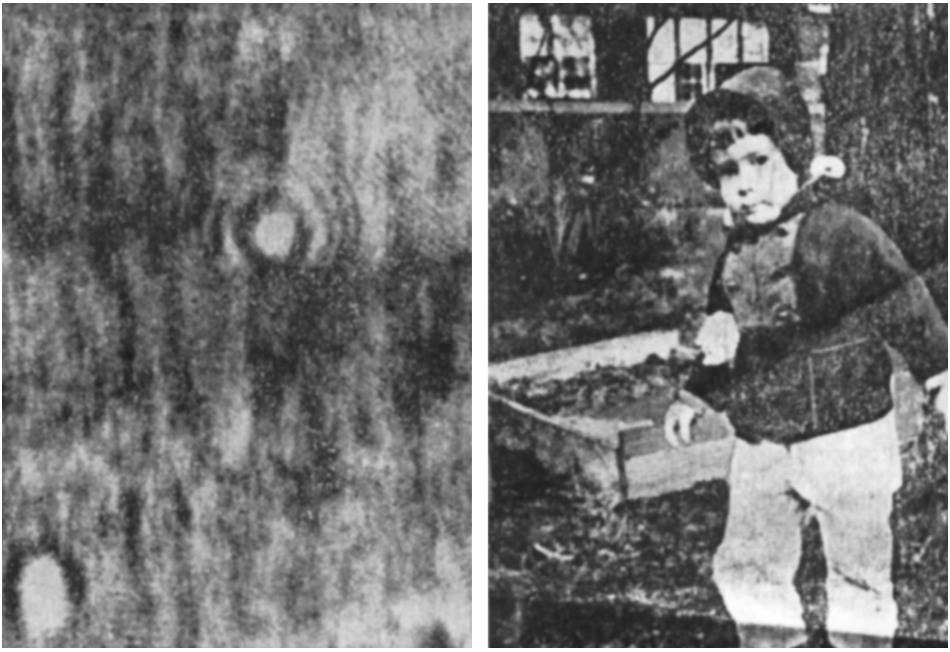

**Fig. 4.** The American Institute of Physics press release images of December 5, 1963, for "lensless photography," with the hologram on left and the reconstructed image of Emmett Leith's daughter, Kim, on the right. *Credit*: Courtesy of Professor Emmett N. Leith.

Subsequently, local editors and newspaper readers must have searched in vain for further points of comparison between the hologram and reconstructed photographic image, failing to perceive the much more complex relationship between the two.

*The New York Times* and *Wall Street Journal* covered the story in December 1963, competing with the Kennedy assassination for space.[21] The *Times* interviewed Leith by telephone for over an hour and printed a half-page story. Both newspapers described the unfamiliar process as a two-step extension of photography, with the hologram identified as a smudged, blurred, or "unclarified" negative. This identification as an analog of photography persisted, with the *Times* devoting a half-page article in its *Sunday Photography* section to holography.[22] This portrayal, however, was unfamiliar to the Willow Run workers, who struggled to link their holographic concepts and interpretations to photography. Indeed, the appeal of a hologram was its *dissimilarity* to a photograph. Consequently, these first reports of lensless photography emphasized its novelty, its reliance on "high science," and its perplexing nature.

A longer article that month by Leith in *Science Fortnightly* also vaunted the three-dimensional capabilities of the new technique. In it he struggled to link the classified research to other technological understandings, highlighting both microscopic applications and miraculous three-dimensional imaging. Unfortunately, the properties of the off-axis hologram seemed too novel for straightforward comprehension by amateur photographers:

> The resulting hologram is then capable of projecting a three-dimensional image in space – and no screen is required. The projected "image" hangs in midair. The technique is limited to indoor photography, since it requires coherent (monochromatic, in phase) light to work. Sunlight is not coherent.[23]

This lack of fit with photography engendered bafflement. Skepticism or disbelief arrested many readers. Upatnieks recalled "numerous doubts expressed by inquiring reporters," which prompted him and Leith to decide to make higher-quality holograms as demonstration pieces.[24] By March 1964, they produced the first widely seen hologram: an image of a toy train.[25] Earlier, during the winter of 1963-1964, with impressive holograms to show off even then, the news about three-dimensional imaging began to raise the profile of their research, something that had not occurred at Willow Run since the announcement of the SAR system in 1960:

> It was a type of imagery that had never before been seen. People sat up and took notice, people in the laboratory looked at it in astonishment, the management came in and looked at it, and the Director came in, people outside the university came and looked at it.[26]

Upatnieks and Leith demonstrated the technique to scientists and engineers publicly for the first time in April 1964 at the spring meeting of the Optical Society of America. They began their explanation of it with the photographic analogy, but found that it provided little insight:

> To photograph an object without using lenses, first an out-of-focus picture, called the hologram, is obtained.… The object will appear as though the observer were looking at the scene through a window the size of which is the same as that of the hologram. Parallax, depth of focus, and stereo effects are evident.…[27]

Their seven pages of notes used photographic language mainly in the introduction and conclusion, touting their technique as an extension of photography. This cocooned the alien concept, which they described in these sections almost entirely in terms of its effects.* It was precisely the nonphotographic characteristics, however, that evoked the strongest reactions from listeners and viewers.

At the end of their fifteen-minute paper, Upatnieks announced that an example of their work was on display. The laser manufacturer Spectra Physics, which had a display suite in the hotel, allowed them to display the hologram of a toy train there. When he and Leith reached the room, they found a long queue of optical scientists out of the suite, down the hall, and around the corner. Many of these specialists were disbelieving or confused. The toy train appeared perfectly real and yet could not be touched behind the photographic plate. Several questioned where it was hidden, or sought the mirrors

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* Upatnieks and Leith used the term "wavefront reconstruction" only twice in their text, while "photography" and "photograph" (as noun or verb) appeared six times. Their presentation focused on how reconstructed images could be viewed and photographed, which further allied the techniques of photography and wavefront reconstruction. By contrast, they used the word "hologram" twenty times in their text.

that had produced the illusion. One even feared that his eyes had been damaged by the laser light; even for optical scientists, lasers as sources of illumination were still a distinct novelty.

The photographic analogy launched by the AIP press release proved difficult to quash despite its difficulties. One discordant description appeared in a Detroit newspaper on Sunday, February 23, 1964.[28] Along with descriptions of side-looking radar and "death-ray" lasers, the article devoted a few paragraphs to lensless photography. It emphasized attributes that had been unmentioned in earlier reports:

> The light bounces from the subject, into a mirror and onto film. The result is a transparency that looks to the eye like a buttermilk sky. But when laser light is played upon it, the original scene takes shape in three dimensions. An unusual property of the transparency is that the whole or any part of it contains the entire picture. Tear it up and any fragment of it will reveal the total picture under laser light.[29]

And, as Upatnieks and Leith pointed out:

> The hologram, which is the first recording on film, ordinarily is considered to be the negative. Yet the reconstruction gives a positive image. If a contact print is made of this, again a positive reconstruction is obtained. It is impossible to obtain a negative reconstruction.[30]

Yet another unintuitive property of the hologram was that the contrast of the reconstructed image proved to be independent of the contrast of the film: High or low-contrast film could reproduce an equally faithful – and extremely broad – tonal range. "This, of course," they noted, "is not the case in ordinary photography." [31] The "lensless photograph" or off-axis hologram was becoming ever more curious. It showed no trace of an image. It could be created only by special laser light. It always yielded a positive image, and a full picture from any fragment of the hologram. In its three-dimensional guise, lensless photography began to look very unlike photography indeed.

By a combination of demonstrations, conference communications, newspaper interviews, and journal publications, Leith and Upatnieks continued to spread the word. They submitted an expanded version of their paper to *The Journal of the Optical Society of America* in June 1964; it was published that November. This publication, too, was preceded by an AIP press release that proclaimed the advances in wavefront reconstruction that had been achieved over the previous year. It focused on the unfamiliar three-dimensionality of the image, and especially parallax – this ability to look around and over the objects in a reconstructed scene demarcated the Leith-Upatnieks technique from any earlier form of stereoscopy. Further, its association with the laser accentuated its modernity and mystique. A final frisson of the mysterious for uninitiated readers – but representing the developers' own insights drawn from radar research – was provided near the end of the press release: "The process can be thought of as capturing and storing the light rays and releasing them at some later time, whereupon the imaging process is carried to completion." [32]

Gabor had stressed the two-step nature of the process fifteen years earlier. For the Willow Run researchers, two-step imaging was an essential property of SAR systems. Unknown to them, it also was a theme that Denisyuk had developed in Leningrad a year or two earlier. Now, however, wavefront reconstruction originating and ending with visible light made the idea of "storing a wavefront" more obvious. The notion of a "window with a memory" was particularly apt for the Leith-Upatnieks hologram, but one that further strained the analogy to photography.

A reporter covering a conference in Boston that fall gave a first-hand report of seeing a hologram, reciting what was to become a familiar litany of its counterintuitive properties:

> When you looked at the hologram, illuminated from behind by a gas laser, you saw the train and conductor toys [*sic*] right there on the table, in three dimensions. If you wanted to see what was behind the little man, or in front of the toy locomotive, you simply moved your head to see them. No need for viewing glasses, double images or squinting.…
>
> Because there are no lenses, each point on the object is recorded all over the photographic plate. So you can take a hologram and cut it in half – or in a dozen pieces – and each piece will still show the entire object, from a slightly different point of view, with only a little loss in sharpness.[33]

## The Holography-Photography Analogy: Precedents and Predictions

The hologram had undergone a metamorphosis from an incomprehensible intermediate component in Gabor's "holoscope" into an exciting but even more baffling artifact. The off-axis hologram in its new guise as a lensless photograph was able to recreate realistic and unsettling three-dimensional images; it somehow encoded details of the entire scene in every portion of it; and it froze time, releasing that image when prompted again by the exotic new technology of the laser beam. Wavefront reconstruction had been recast as a vision of the future, no longer constrained by the goals of microscopists or even hinting at the optical-processing research that had given birth to it. Divorced from its roots, it began a new life as a modern branch of photography that seemed guaranteed to provide continuing awe, commercial applications, and success.

The initial cultural response to Leith-Upatnieks holograms, in fact, closely mirrored that prompted by daguerreotype photographs when they were first announced to the Paris *Académie des Sciences* and *Académie des Arts* in August 1839. As one account related:

> There was a great deal of excitement, and the crowd's reaction to the announcement was intense and immediate: within hours every optician in town was besieged with people trying to obtain cameras in order to share in the wonder of the new art-science.[34]

The analogy between holography and photography went further, however. Besides their reputed technological similarities and their initial popular acclaim, predictions of progress began to build upon this analogy. Here *technology* and *function* were a less significant link than perceptions of a cultural trajectory.

Thus, the historical precedents of photography argued that holography, too, would enjoy growing popular acceptance and economic success. The earliest commercial promoter of holography was Keeve (Kip) Siegel (*ca*. 1920–1975), a Willow Run physicist and administrator who had established his own firm, Conductron Corporation, in Ann Arbor in 1960. By 1966 its optics group of some forty people was responsible for SAR contracts and holography production and development, with a half-dozen holographers intimately involved in extending the art. An example of Siegel's typical spiel for commercial holography appeared in a speech he gave to new employees:

> If you went to a classroom, and were taking pictures of one of your children, say, playing in kindergarten, and one of the children ran behind the other children, instead of stopping taking movies, you continue taking movies, and then when you get home and you show those movies of your children, when your child has ducked behind other children, all you need to do is move your head, and you can follow your child as your child is running behind other people. You'll find when you see the hologram, you'll be able to see behind other objects. There are other properties associated with holograms that you'll be able to see, demonstrated at the Hanover Fair in Germany, and the IEEE [Institute of Electrical and Electronics Engineers] meeting in New York, and we've been demonstrating all over the world – you can take off half the picture, cut off half the picture, and you still have the ability to see the whole picture, because now you can look around corners and you have the effect of having enough intelligence every place in the picture to get the whole picture.… I am hoping that by the year 1976 that the United States will have, as far as new products are concerned, only 3-dimensional television and 3-dimensional movies on the market. I would not expect 2-dimensional processing, 2-dimensional television, 2-dimensional home movies to continue – that's my personal belief. I don't think people will buy things that are antiquated.[35]

Siegel's speech is noteworthy in several respects. His use of the term "intelligence" for "information" hints at the close association between military and commercial research. His portrayal of holography as a future consumer industry relied on his implicit faith in scientific, technical, and economic progress, which he shared with his colleagues. That faith rested on the history of photography, cinema, and television, which he portrayed as inexorably advancing. Yet his technical claims far exceeded the capabilities, or even expectations of his engineers: His commercial forecasts diverged from their own technical extrapolations. Nevertheless, his showmanship and promotion of the new medium flavored subsequent forecasts for a generation.

Counterculture holographer Lloyd Cross (b. *ca*. 1934, figure 5), also a former Willow Run engineer and Siegel's sometime employee, too had plans to market holography.[36] Cross reshaped the photographic analogy, and imagined the medium being developed as a cottage industry by amateurs, instead of by corporations and tycoons:

> Within a year or so, I think there will be hundreds of little holographic studios all over the country with people exploring holography the way photography was explored. Commercial holography is now where photography was in the mid-19th century, and the next step will be to develop a simple, cheap pulsed laser – this will do for popular holography what the flash bulb did for photography.[37]

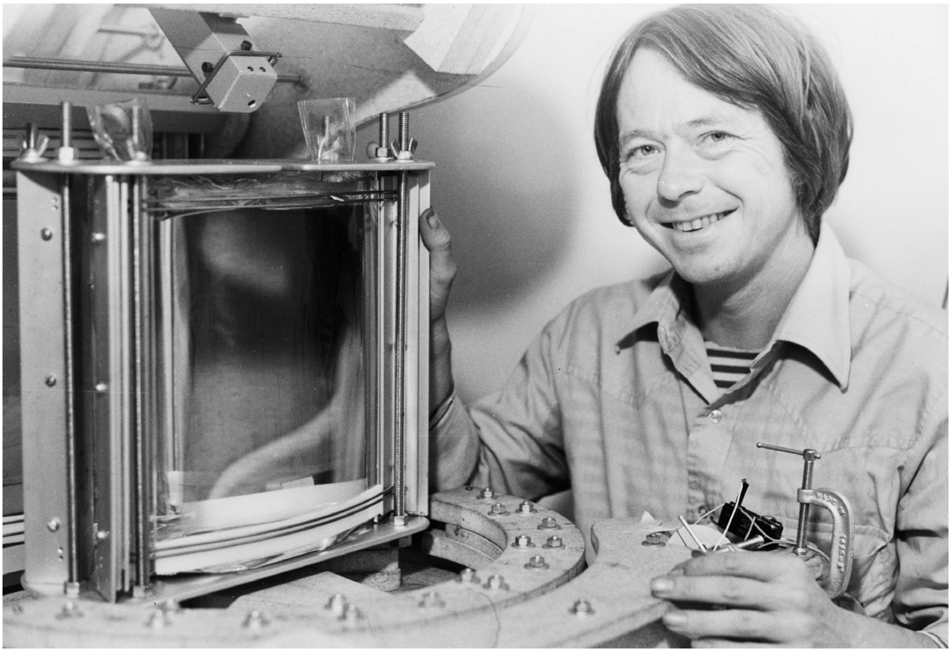

**Fig. 5.** Lloyd Cross (b. *ca*. 1934) with oil lens in 1977. *Credit*: Courtesy of the Massachusetts Institute of Technology Museum, Cambridge, Massachusetts.

Academic holographers cited the same parallels. In 1975 Tung Hon Jeong (b. 1936), a physicist and college professor who promoted holography as an educational medium for undergraduates and artists, preached that progress was inherent:

> Photography began as a highly technical process, with contributions from many individuals. It suffered through a period of immense technical difficulties, having unclear and monochromatic images; it then acquired motion, sound, and color; finally, it became *simple*. Holography, after the initial discovery by Gabor in 1947, lay dormant until the sixties. It then went through a period of development by physicists and engineers, with their multi-ton granite stones and mysterious laser beams. Within the last decade, it has evolved into new formats, developed new and simple techniques, and incorporated motion. We can soon expect true color.… If you marvel at how photography has arrived, wait and see how far holography will go![38]

This was an inaccurate summary of the history of photography, and offered few convincing points of comparison with holography. Yet, such messages as Jeong's were influential in inspiring a generation of amateur and commercial holographers.

## Holography and Stereography

Nurturing the analogy between holography and photography had further consequences for the historiography, aesthetics, commercial exploitation, and technological forecasts of the former. For example, holographers and promoters of the medium for imaging purposes commonly argued that the cultural history of holograms had important parallels to that of other imaging technologies, especially the stereoscope. The Scottish physicist David Brewster (1781–1868) first exhibited the stereoscope at the British Association meeting in Birmingham in 1849, and the Parisian optician Louis-Jules Duboscq-Soleil (1817–1886) subsequently fabricated a number of these instruments. Then, when stereoscopic daguerreotypes were shown at the Great Exhibition of 1851 in London, Queen Victoria ordered stereoscopic viewers and photographers hopped on the bandwagon. Within a decade, hand stereoscopes and thousands of stereoscopic views were available, with patents reaching a peak during the 1870s. Regional practitioners produced stereoscopic images for local audiences, while national firms produced them to extend sales and give viewers a sense of worldly sophistication. The subjects were wide-ranging: from landscapes, to monuments, to educational, cultural, and humorous topics. Companies around the world were established to exploit the fad. By 1862, about a decade after being introduced into the United States, it has been estimated that there were over one thousand commercial photographers in America producing stereograms, a figure that commentators have suggested was roughly the number of active holographers in the 1980s.[39] Thus, the similar rate of expansion of practitioners, and of popular users, suggested that eventually holographic imagery would be ubiquitous.

The rhetoric accompanying the introduction of the stereoscope during the 1850s also appeared to mirror aspects of the introduction of holography over a century later. Stereoscopic images were awe-inspiring and shocking, just as were holograms. Historian Harvey Green has described stereograms as provoking "at once wonder, exuberance, hesitation and confusion." Moreover,

> the three-dimensional quality produced when an obviously two-dimensional image was viewed through the proper apparatus occasioned an intensified debate on the nature of reality and truth, art and science. In both Europe and America, analysts wrote often contradictory explanations of the nature, possibilities and power of the new photographic process. For some, the stereoscopic image was truth, fact.[40]

Stereo photographs were vaunted for their "honesty," because they could not be readily retouched by photographers (retouching stood out from the plane of the subjects, making artifice detectable). Pulsed hologram portraits* proved difficult to market for precisely the same reason.[41] Moreover, stereo photographs were described as more complete and beautiful than the two-dimensional photographs that had been available by then for more than a decade, and they provided imagery that conventional paintings could not. As Oliver Wendell Holmes (1808–1894) put it in 1859:

> Form [in a stereo photograph] is henceforth divorced from matter. In fact, matter as a visible object is of no great use to us any longer, except as a mould in which form

* A pulsed hologram portrait of a living subject is recorded using a pulsed laser (initially a ruby laser during the late 1960s and more commonly a neodymium laser from the 1980s).

> is shaped.… Matter must always be fixed and dear; form is cheap and transportable.[42]

These debates of the 1850s and 1860s rehearsed arguments that were employed for holography a century later. But of most significance for the historical analogy, stereography did not endure. As historian Howard Becker has argued,

> we usually study successful artistic innovations, those which not only developed a national or international culture around the production and use of their typical products, but also persisted and became part of the main stream of work in that medium or genre. But stereography … eventually declined, and turned into a dead end.[43]

While stereography diffused into popular culture much more successfully than holography did during the following century, ultimately both were victims of changing fashions and competition from other media.

Stereoscopic views lost popular appeal by the 1890s. Publishers sought to extend the market, producing color stereographs by three-color lithographic printing, but the experience of stereoscopic viewing had become distinctly unfashionable by the First World War. Nevertheless, the market was recaptured a generation later using a repackaged form of the technology: The View-Master, a molded Bakelite stereoscope used to view seven pairs of color transparencies mounted on a cardboard disc, was introduced at the New York World's Fair in 1939 and proved popular, particularly when it was retargeted for children in the 1960s.

Amateur stereography also became possible after the Second World War with the introduction of the Stereo-Realist in 1947, as well as subsequent competing stereo cameras, and endured as a niche hobby until the middle of the 1950s. Although stereo box cameras and folding cameras for amateurs had been available since the beginning of the twentieth century, these postwar cameras usually were used to produce stereo color-slide transparencies, which permitted more straightforward commercial processing, and were free from the *démodé* associations of cardboard-mounted stereogram photographs. At about the same time (1952–1956), 3-D films boomed in popularity as commercial studios sought to compete with early television broadcasts. Two other three-dimensional media rising in popularity during the 1950s were the anaglyphic (2-color) comic for children (1953–1954), and the Xograph or lenticular-screen image (1952). Subsequent interest in 3D imaging was more muted. A notable example was the Nimslo camera system, a stereo camera combined with commercial processing to yield lenticular photographs, which proved to have a limited market appeal during the 1980s.[44]

Most of these physics-based technologies evinced a trajectory of popular acclaim, declining interest, niche novelty applications, and a transformation for the children's market.[45] Holography, as an imaging medium, followed a similar, if less commercially successful path. Art holograms were exhibited from early 1970s, and pulsed holographic portraits became more common a decade later, but children's products and product packaging dominated the commercial market for holograms after inexpensive and low-quality holograms could be made from embossed reflective substrates. With the proliferation of embossed holograms, their higher-quality predecessors largely disappeared and imaging applications lost popularity.*

## Holography and Art

Artists taking up holography discovered that the medium and its trappings were unfamiliar and disquieting. Margaret Benyon (b. 1940), the first artist to produce her own holograms in 1969, dismissed her first show a decade later:

> The very first phase was a false start. I thought I could continue in holography the preoccupations as a painter which led me into it. I quickly discovered after the failure of my first show in 1969 that I could not do this and that I should have to go back to square one. So initially I was concerned to use only those aspects that were exclusive to holography, introducing people to unfamiliar notions about space with time-reversed imagery or double-exposures in which solids seem to share the same space, or non-holograms, which play havoc with received notions of surface, volume, part and whole.[46]

Painting, photography, and holography commenced a diffident *ménage à trois* during the 1970s. But art critics, as well as the public, were ambivalent about the aesthetic content and uses of the medium. Categorizing holography was a central difficulty, and a few commentators eschewed photography completely. A review in the *Chicago Tribune* in 1977 noted that a hologram is "neither painting nor sculpture but a curious, intangible distillation of the two."[47] The first major American exhibition of art holography was a major show, *Holography 1975: The First Decade*, held at the International Center for Photography (ICP) in New York. This was the most visible display yet of holograms in an artistic venue, and in a city that prided itself on sophistication and art criticism. It attracted mixed reviews. A critic writing in the *Village Voice*, for instance, noted that "so far the medium is more entertaining than it is artistically expressive. But while holography has yet to find its Stieglitz or Steichen, it is plain to see that the medium will continue to lure new and devoted devotees."[48] As the critic noted with his references to Stieglitz and Steichen,** holography was being portrayed as analogous to early pho-

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* Embossing processes, in which an aluminized polymer substrate is thermally or mechanically impressed with height variations to yield a so-called "phase hologram," were developed from the late 1960s and flooded the market from the early 1980s. Image quality is usually unimpressive owing to distortions caused by the flexible backing and blurring caused by reconstruction of the image using white light.

** Alfred Stieglitz (1864–1946) and Edward Steichen (1879–1973), as American photographers who strongly influenced photography as an art form, had no obvious counterparts among aesthetic holographers of the 1970s and 1980s. Both Steiglitz and Steichen contributed prominently to schools of photographic representation such as Pictorialism and the Photo-Secession movement, and developed media (such as gum bichromate and glycerine printing), new subject matter (such as landscape photography and fashion portraiture), and new styles of representation. By contrast, no recognized school of holographic representation has been identified up to the end of the twentieth century, although aesthetic holographers pioneered certain artisanal techniques such as the employment of dichromated gelatin as photosensitive emulsions.

tography, and as an aesthetic medium in the making. The location of the exhibition in the International Center for Photography was the strongest indication of this claim.

Nevertheless, a scathing rebuff for the fledgling subject appeared in *The New York Times* one month later. Art critic Hilton Kramer (b. 1928) archly identified the culture of holography as one defined by second-rate subjects and dubious practitioners:

> It is, to judge by the present exhibition, a gadget culture, strictly concerned with and immensely pleased by its bag of illusionistic tricks and completely mindless about what, if any, expressive possibilities may lie hidden in its technological resources. There are, to be sure, a few artistic attempts here at abstraction and pop art and the familiar neo-dada repertory, but these are even more laughable than the outright examples of kitsch. Much of the work has, I gather, been produced not by artists but by physicists professionally involved in holographic technology. The physicists appear to favor objects out of the local gift shop, whereas the artists do their shopping in provincial art galleries, and both, it seems, are much taken with television commercials. It is difficult to know which is the more repugnant: the abysmal level of taste or the awful air of solemnity that supports it.[49]

There was, indeed, a danger in the organizers' inadequate differentiation of "art" from "clever imagery" for critical consumption, but as some artists noted then and afterwards, such distinctions were not trivial to judge. Cornell Capa (b. 1918), the Executive Director of the ICP, responded to Kramer, largely concurring with him:

> Mr Kramer is completely right about holography. He criticizes holography for its overly-complete depiction of reality.… To this we can only plead pictorial poverty; there just isn't enough holography around to permit the same kind of critical judgments that go into an exhibition of pictures in which images, rather than their processes, are the subject-matter. And suppose all of us – exhibitors and critics alike – just happen to be wrong. Suppose that among the several thousand people who have already experienced the "esthetic kick of a postcard from Montauk" there is just one person who has formed one idea that might make meaningful holography feasible. It isn't impossible, and that's why we're here.[50]

In rebuttal, Jody Burns, the co-organizer of the exhibition, drew the now-familiar analogy to early photography:

> I believe that one of the important functions of the International Center of Photography is to expose possibilities, such as this new visual experience, holography, just as it was important to introduce photography in 1839, to potential artists who may transform and advance a technology ever closer to greater artistic expression.[51]

A second wave of exhibitions created a certain solidarity among holographers, as illustrated by an influential British exhibition, *Light Dimensions: The Exhibition of the Evolution of Holography*, which was held at the National Photographic Centre of the Royal Photographic Society (RPS) in Bath in 1983. Like the earlier British holography shows *Light Fantastic I* and *II* (1977–1978), it attracted large audiences, estimated at a half-million visitors over its year-long run. The RPS, its principal organizer, became an institutional supporter of holography following the formation of its Holography Group that year, which brought together British scientists, artists, and amateur holographers. In his preface to the exhibition catalogue, RPS President Christopher Roberts drew strong parallels between *Light Dimensions* and the first major photographic exhibition, held in London in 1852–1853. That show, supported by the Society of Arts, had displayed 800 photographs and had triggered the formation of the Photographic Society in 1853, which has held annual exhibitions ever since. With an eye to history and the Society's own traditions, the RPS now supported the holography show, declaring that it was meant

> to evoke all the excitement of those early photographic exhibitions of the 1850s because, as they were, it is involved with a developing technology giving to the artist new possibilities of self-expression, to the technologist new applications and to the uninitiated viewer, a new experience.[52]

Its organizer, Eve Ritscher, drew similar analogies between the history and impact of photography and holography.

Photographers and holographers, however, had an uneasy relationship. Photographers did not accept that this new technology represented the future of their medium, or even shared close affinities with it. The intellectual roots and implementation of photography shared little with holography. For example, while both used light-sensitive emulsions, holography demanded recording resolution and mechanical stability orders of magnitude better than photography. Photographic firms – particularly Ilford Photographic Ltd in England and Agfa Gavaert in Belgium – pursued the market in holography between the 1970s and 1990s but judged it to be too small and too different from their photographic products to be worth continuing.* There were serious technical limitations: The exposure required a monochromatic and spatially coherent source, which dramatically constrained the size and subject matter of holograms. Nonetheless, holographers strained to maintain the analogy: RPS Fellow Graham Saxby (b. 1925), for example, whose career went from photographic technician to holography teacher, compared holograms of the 1980s to the table-top close-up photographs that had been a fad of photographic amateurs fifty years earlier.[53]

## Conclusions

The physics and technology of holography were successively recast by and for new audiences. The theoretical foundations of the subject were laid in three distinct contexts: the hybrid electron-optical microscopy of Gabor, the wave recording of Denisyuk, and the communications theory of Leith and Upatnieks. From the middle of the 1960s, however, the subject was reinvented and reinterpreted as an extension of photography, which reshaped its meaning and highlighted a subset of its applications.

* Ilford's research, development, and marketing program for holography expanded dramatically in 1983 but ended in 1992; Agfa Gavaert ceased commercial production of holographic emulsions in 1997. Eastman Kodak, which had supplied existing spectroscopic and aerial camera emulsions for holography since the middle of the 1960s, abandoned overt marketing of such products from the late 1970s after expectations of a growing market failed to materialize.

Interpreted as an advanced form of photography, holography was portrayed as the imaging medium of the future, and identified as a technology destined to follow a similar course to that of its two-dimensional precursor. Forecasts predicted rising commercial popularity, first as a cottage industry, then as a corporate product, and finally as an aesthetic medium. At the same time, this depiction of holography deemphasized other, less easily absorbed aspects of its meaning.

While such interpretations led to a rising popular engagement with holography between the middle of the 1960s and late 1980s, its analogy to photography ultimately lost potency. Progress of the new medium over time diverged increasingly from that of early photography. Unlike photography and even its stereoscopic variant, the seeming technical disadvantages of holography were judged to restrict its appeal, and to dominate its compelling imagery. The analogy between photography and holography thus provided the new technology with a foothold, but only a temporary one. From the 1980s, holography followed new directions. The first of these was its growing popular perception as a medium that expressed holism – indeed, as a metaphor for a paradigm.[54] The second was a retrenchment toward scientific channels of inquiry that explored deeper connections with optical transformations.

Over a period of sixty years, then, holography evolved through a series of analogies with prior technologies, and especially as a successor to photography. These analogies had the dual effect of aiding the acceptance of holography by wider publics and, at the same time, of constraining their perception of its potential applications.

The history of holography illustrates how we categorize new sciences and technologies. Its comparison to photography reveals how some definitions of technological similarity and difference are shaped by culture. These categories, in turn, can influence perceived applications or expectations for the evolution of a new technology, and subsequent judgments of progress. They demonstrate how designers, adopters, and observers address a new subject by seeking connections with what they know, and identify it as an extension of recognized capabilities. Thus, the directions taken by a new subject such as holography can be shaped by familiar analogies as well as by the more recognized routes of intellectual exploration, technical improvement, and market need.

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Note: I use the following abbreviations for the archival repositories I cite below:

BL = Bentley Library Archives, Ann Arbor, Michigan

CC = Clark Charnetski collection, Ann Arbor, Michigan (privately held)

IC = Imperial College Archives, London, Gabor Papers

LC = Emmett Leith collection, Ann Arbor, Michigan (privately held)
MIT Mus = MIT Museum, Cambridge, Massachusetts, New York Museum of Holography Collection
Sci Mus = Science Museum Library, London, Rogers Papers
UC = Juris Upatnieks Collection, Ann Arbor, Michigan (privately held)

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