NATIONAL ACADEMY OF SCIENCES

HERBERT EUGENE IVES

1882—1953

A Biographical Memoir by

OLIVER E. BUCKLEY AND KARL K. DARROW

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Any proper biography of Herbert Eugene Ives must perforce begin with a very special mention of his father Frederic Eugene Ives (1856-1937), for the son's career was a consequence of the father's, with many strangely similar details. The elder Ives was born of a farming family, and his father (according to what Herbert Ives has said) was a stern man. Frederic Ives was already apprenticed to a newspaper printer at the tender age of thirteen: it is a testimony to his passion for photography that at nineteen he was director of Cornell University's first photographic laboratory, and it is a testimony to his enterprise that at twenty-five he was running his own business. This business consisted in making half-tone printing plates, the first ever invented, and the invention was his own; his own also was the invention of the half-tone process now in universal use, made a few years later (1885-1886). Later on there was an Ives Kromskop Company, the name of which implies color photography; and his son has spoken of the "atmosphere of color photography" that prevailed in his home. Among his other inventions one finds listed a trichromatic camera, various processes of color photography, a short-tube single-objective binocular microscope, and a "device for optically reproducing objects in both full modelling and natural colors" (the quotation is from the Encyclopaedia Britannica) called a "photochromoscope." These items are cited to show Frederic Ives' devotion to the art of photography and the science of optics, combined with great inventiveness. Devotion to the science of optics and the art of photography were attributes of Herbert Ives also, and he too possessed inventiveness. Honors were lavished on the father in America and Europe, and honors were also lavished on the son.

After the lapse of three-quarters of a century, it can probably never be ascertained why Frederic Ives, born and bred a New Englander (he was from Litchfield, Connecticut), set up his business and his home in Philadelphia. This decision made Herbert Ives a Philadelphian by birth and by predilection. There he was born on July 31, 1882; there he spent his pre-school years, most of his school years and all of his college years; thither he returned after three years of graduate study and four years of employment in other cities, there he worked for six years, and there he might have lived to the end of his days but for World War I, the effect of which upon his life will presently be recounted. Ives was very fond of Philadelphia, as also of London; for he had a rare opportunity to know the British metropolis, since his father's enterprises took him to London for periods adding up to about four years. London captivated Ives by its history, its antiquities, its libraries and its museums. He says of himself that he was a frequent visitor to its museums and art galleries, a taste rare in a teen-ager. Later he was heard to say that London would be the best place to spend one's retirement. This intention, if it ever was an intention, he did not carry out.

For information about Ives' earlier years—and some of his later ones—we have the great advantage of possessing a typescript of his answers to a questionnaire, apparently one circulated by the National Academy of Sciences. The exact questions are missing, but one can make plausible guesses as to what they must have been. Surely it was in answer to a question about his childhood that he replied as follows: "Father's experimental work, carried on at home in third floor of house, was continual centre of interest. Enforced attendance at local Methodist Church under continued and growing protest. Became incessant reader, particularly of history. Pronounced interest in drawing. No interest in athletic games. Collected coins." The next question must have been about his pre-college education, for here are extracts from his answer: "Philadelphia public schools to 11th grade, interrupted by year in England (1892) where attended University College School, London. Attended Lawrence Sheriff School at Rugby, England, 1897-98. Franklin Institute Night School of Mathematics, 1899-1900 while working in father's Philadelphia business (Ives Kromskop Co.). Preferred science and drawing, disliked Latin intensely, considering it useless, but did well with French and German. Home occupations: reading of Spencer, Darwin and Huxley with avidity." What a studious youth emerges from these lines!

We now leap forward to a further passage in his responses to the questionnaire. Here is a paragraph which will be read with interest by every physicist, perhaps with surprise and disappointment by some teachers:

"My interest in physics, particularly in optics, is the direct outcome of my early surroundings, where I was constantly in contact with the active and intensive work of my father in color photography. I do not believe I would ever have gone into physics professionally if my introduction to it had been through school and college courses. These latter I found difficult and uninspiring, with no hint in them of the adventure and spell that I sensed in my father's work. My special interest in optics is undoubtedly connected with my early love of drawing, which I have lately revived as an avocation in oil painting, particularly portrait painting. My most productive training in applied optics was acquired as a worker, and soon foreman, in the Ives Kromskop Company in Philadelphia (1898-1901) devising, constructing and manufacturing apparatus for color photography."

The approach to physics which Ives has so vividly described in those lines may once have been common; it is bound to become rare as the years go on (nobody works as a youth in his father's cyclotron-factory or atomic-energy plant!). Incidentally we learn from this that Ives' transition from school to college was not by the normal route of a high-school diploma, but by a period of scientific employment. He supported himself throughout his student career at the University of Pennsylvania. He entered it in 1901 and emerged a Bachelor of Science in 1905, having in the meantime been admitted to Phi Beta Kappa and Sigma Xi, figured on the University Debating Team, acquired "sophomore and senior honors" and served as President of the "Zelosophic Literary Society." Now he was ready for his graduate work, and for this he went elsewhere.

The Johns Hopkins University at Baltimore, not so long before, had been the leading American university in graduate work; in 1905 it remained outstanding. Why did Ives choose it? Again we are reduced to guessing, but again the guesses are plausible: proximity to his home, the availability of a teaching fellowship and the presence at Johns Hopkins of Robert W. Wood, then the greatest authority on light in the United States and perhaps in the world. Ives spent at Johns Hopkins the usual term of three years (1905-1908) before he attained his doctorate. From this period date his first three papers. The formative influence of the years spent with his father is apparent from their topics. The first two (both published in *The Physical Review*) relate to improvements in methods of color photography, but the methods are different in the two cases. The earlier paper (1906) pertains to Wood's device, which depended on diffraction of the colored light by gratings; the later (1907) to Lippmann's scheme, which depended on the formation of standing light-waves in the photographic film.

It is exceptional for a graduate student to publish two full-scale papers before he writes his doctoral thesis. Apparently Ives did, for his thesis is the third of his papers: under the title "An Experimental Study of the Lippmann Color Photograph" it appeared in the *Astrophysical Journal* in 1908. It was of durable importance, and the reader will agree that it merits the space that we here give to it.

The Lippmann process of color photography consisted in forming standing light-waves in the photographic film. For this purpose the film was pressed against a reflecting surface (a mirror of mercury).

A beam of light projected against it traversed the film twice, once going and once coming back. Thus standing light-waves were formed in the space occupied by the film, and these imprinted a periodic structure on the film itself. Suppose for instance that the beam is of monochromatic yellow light: the structure imprinted on the film has a period equal to half the wave-length of the light (normal incidence being presumed), and *such a structure has a specially strong reflecting power for light of the same wavelength as produced it,* so that daylight reflected from the film will be strongly tinged with yellow. One can see, in a general sort of a way, that incident light of a variety of wavelengths might be expected to produce a periodic structure containing the periodicities of the various wavelengths, so that daylight reflected from the film might be converted by this selective effect into something resembling the spectral composition of the original incident beam. And so it was; but the result was not so good as might be desired, and Ives set out to improve it.

In his Rumford lecture forty-three years later, Ives was to say: "Having been brought up in an atmosphere of color photography, this was a problem that excited my interest, and I chose a study of the Lippmann process for my doctor's thesis at Johns Hopkins. Fate played into my hands, for just at that time Ramón y Cajal reported the observation that the structure of Lippmann films could be enlarged to observable dimensions by the simple expedient of soaking them in water, whereby they were expanded many times and brought into the range of ordinary microscopic observations." This procedure showed that the structure extended only a few wavelengths deep into the film, not nearly far enough for what a spectroscopist calls good resolution. To quote again, "Some knowledge of photographic processes, acquired in a home where a photographic dark room was considered as necessary as a kitchen, gave a hint to a productive line of inquiry." What Ives then did was to substitute a slow-acting developer for the previously used quick-acting one, so that the film got wet clear through before the developer functioned. Now the structure extended deeper into the film, but still not deep enough. But where it stopped, it stopped abruptly: and this suggested to Ives that the limit was set by the depth to which the sensitizing dye (used to make the film color-sensitive) penetrated into the film. He put the dye into the emulsion before the plate was "flowed"; and lo! the laminae extended clear across the film! One further step had to be taken. The film was so nearly opaque that only the few top laminae were operative. "Here again a familiarity with photographic processes came to the rescue"; by the use of mercuric chloride, Ives converted the film into "laminations of alternating higher and lower refractive index, transparent to light from the whole depth of the film." The problem was solved. The reader should consult Ives' Rumford Lecture (Proceedings of the American Academy of Arts and Sciences, Vol. 81, No. 1, 1951) to see the photographs which show how well he solved it. Standing waves were again to play a transcendent role in Ives' study, more than twenty years later, of the photoelectric effect. We shall come to it soon.

We shall not be able to go on describing Ives' papers one by one, for a very good and striking reason. Ives' "literature" totals no fewer than two hundred and fifty (!) papers—mostly in scientific journals, but among them are also contributions to encyclopaedias, textbooks, and books published as groups of chapters by different authorities under a single editor. Of these, almost exactly half date from the period before 1919, a crucial date in Ives' personal history.

Now it is time to mention Ives' first three positions. He served at the National Bureau of Standards for one year (1908-1909); went thence to the Nela ("National Electric Lamp Association") Research Laboratory at Cleveland for three years; then to the United Gas Improvement Company in his native city of Philadelphia for six years. Most of the papers which he published during his sojourn at these three laboratories were in the field of photometry, but there are others: luminous efficiency, visual acuity, artificial daylight, spectroscopy, color mixture equations, "a precision artificial eye," "simple methods of spot-lighting in the home," persistence of vision, the mechanical equivalent of light. Here we mention his study of the light of the firefly, of which (in collaboration with W. W. Coblentz) he was the first to observe the spectrum. Dr. Deane B. Judd, of the National Bureau of Standards, has kindly provided an analysis of Ives' work in photometry and colorimetry. We quote:

"Dr. Ives has made important contributions to photometry and colorimetry. His extended studies of the luminous-efficiency function for various conditions of observation and methods of determination disclosed that equality-of-brightness photometry agrees closely with flicker-photometry for fields of small angular subtense (2°) and photometric and surrounding fields of high luminance, and these conditions are standard today and implicit in legal definitions of standards of light throughout the world. His papers on the transformation of color specifications from one set of primaries to another are largely responsible for introducing modern tri-stimulus colorimetry into this country. Color rendition of objects by chromatic light sources is a subject of much current interest and study. The three-components theory of chromatic adaptation currently in greatest favor was completely and clearly explained by Dr. Ives in 1912."

In 1918 Ives left his position at the United Gas Improvement Company to enter into war work. The story as related by Mrs. Ives is well worth recounting; it illustrates Ives' self-sacrificing patriotism, and also exemplifies an experience which befell many a physicist (not to speak of members of other professions) during World War I and World War II.

The day after Christmas (1917) Ives was asked to come down to Washington to see Dr. R. A. Millikan. He was to stay two nights; he stayed three, and then "telephoned from the junction that he'd be home in half-an-hour and he'd like me to think over his going into the army for the duration of the war. 'How long will it last?' I naturally asked. 'Two years, or three, or five or seven—no one knows.' As I had three children to feed and put to bed, I was barely through when he came in. 'What have you decided?' he asked. 'I haven't had a minute to think about it' I naturally said, 'but *you* will have to decide for yourself, of course.' 'They need me and if you agree, then I'll go down on the first train tomorrow, and not go back to United Gas Improvement again. My assistant there will be out here in half-an-hour and I'll tell him which things are mine, which work at the laboratories can go on, etc.' He had already telephoned the Director, who agreed that Herbert would be needed by the Government, but said that if he as head of research left, they could not guarantee to hold the laboratory together in his absence, especially as more of the men would be called into the service before long. So he went in [to war work] knowing that he would have to chance there being any research plant to come back to. The company did let it lapse, and he did have to hunt for a new job when he left the army.

"And he was the only man on our block with children who did go into the service. I was always proud of him, but it did mean lots of scrimping, even of food, to pay a stepgrandmother's annuity and live on the remainder of a captain's pay, with two households to keep up. Costs were so high that he got to eating a chocolate bar for breakfast, to save enough for lunch. But he did what he thought right, and never complained. And it certainly was hard to get any job at all when everyone was coming out of the army at once; and no one would let him teach, since he hadn't come from a teaching job in the past. He did advise Sherman Fairchild for six months or so, before going to the Bell System; but he preferred a real laboratory job."

The sudden summons, the quick decision, the willing acceptance, the long absence from his habitual work—these are familiar events in the lives of physicists whose careers included either war; complicated in the case of Ives by the scanty pay and by the collapse of his laboratory. A mild anecdote may be introduced here. Some years later, while Ives was dining with a group of his colleagues at Bell Telephone Laboratories, the conversation turned to the world tour which the Prince of Wales was making at the time, and one of the group remarked enviously that the Prince had had about every conceivable experience. Ives grimly commented "He never had the experience of hunting for a job!"

As to Ives' war work, he was in charge of aerial photographic research for the United States Army. He was captain in the Aviation Section of the Signal Corps; his enterprises ranged from developing cameras able to withstand vibration of airplanes to methods for piercing fog. From the work of this period came his book *Airplane Photography,* 1920. He was discharged from the army with the rank of Major in the Reserve Corps.

Ives' experience of job-hunting in 1919 was evidently not a pleasant one; but it was his last. When he entered Bell Telephone Laboratories (then the Engineering Department of the Western Electric Company) in that year, he entered upon the position that he was to hold until the day of his obligatory retirement at age sixty-five—that is to say, for twenty-nine years, more than three times as long as the sum of all his previous periods of employment. He also moved from a Philadelphia suburb to Montclair, New Jersey, and into the house (32 Laurel Place) that he was to occupy for the rest of his life.

The first task assigned at Bell Telephone Laboratories to Ives was research in the behavior of electrical contacts, a never-ending problem of telephony. It was not a subject of great attraction to him, nor did he make many significant contributions to it, as is evidenced by the scarcity of his published papers relating to it. It did not draw upon his previous experience nor utilize his outstanding talents effectively. Fortunately there was other opportunity close at hand to draw more directly upon his dominant interest in matters optical, such as research in the problems of picture transmission. It is possible that Dr. Harold Arnold, who hired Ives, had this prospect in mind at the time.

From the earliest days of electrical communication the transmission of visual information as well as sound had been a goal of inventors and research workers in electrical communication; but until the advent of the art of electronics with its vacuum tube amplifiers and other needed devices, little practical advance was possible. The blossoming of electronics after World War I made picture transmission a practical possibility and opened the door to television, the long-dreamed-of transmission of visual images. Ives undertook work in this field with great zeal, and to it he devoted many productive years in laying a sound foundation of physical knowledge basic to practical application.

Essential for any electrical transmission of visual images is a means to convert visual information into electrical impulses that can be transmitted over wires or by radio waves. Such a means is the *photoelectric cell* or *photocell*. The development of photoelectric cells became one of Ives' main interests, and he made substantial contributions to the understanding of photoemission of electrons (we shall touch on these later) as well as the development of practical photoelectric devices. The photocells which were evolved as a result of these studies became standard devices of great sensitivity and reliability. Their availability for research both inside and outside the Bell System contributed significantly to scientific advance in many fields of research.

A practical application of great immediate interest to the Bell System was the transmission of pictures over telephone lines. This development matured to the point of demonstration of commercial service in 1924. Interest in it was heightened by the Republican and Democratic conventions at Cleveland and New York. During these conventions hundreds of photographs were transmitted and copies furnished to the press at the receiving points. Although picture transmission had been the object of experiments of inventors for many years, this was the first time that a system had been perfected to such a degree that pictures useful for press purposes could be sent rapidly and efficiently over long telephone circuits. Like nearly all developments of Bell Laboratories, this system was the product of a group effort drawing from many departments with a great variety of essential skills. Ives was, however, definitely the leader in the technical aspects of this project, and there he laid the foundation for subsequent developments of wide importance. Today picture transmission is commonplace and there are many systems in operation, but all have drawn from the contributions of Ives to the fundamentals which he recognized and applied in this first practical system for the transmission of pictures over telephone lines.

Close on the heels of picture transmission came television. Ives' work on television bore fruit in the first practical demonstration of transmission of vision over substantial distances, when in April, 1927, visual communication by wire was set up between Washington and New York. Radio transmission over a shorter distance was also demonstrated. The apparatus employed was crude in comparison with that of the later art but it served its purpose admirably and gave to the telephone engineers a starting point for the development of television transmission systems.

The story of this first demonstration of long-distance television is best told in Ives' own words written on the twentieth anniversary of this historic occasion (Bell Laboratories Record, Vol. 25, p. 190, May 1947) and here quoted with some omissions.

"'This afternoon at about three o'clock, connection was made by wire to Washington and the small disc connected. A perfect image was received. Kingsbury, Knapp and Etheridge were seen exceedingly satisfactorily—the first viewing of human beings at a distance of hundreds of miles was completely successful.' This entry, which I find in my log book under the date March 26, 1927, marks the attainment of the first goal of television research in these Laboratories. The trial referred to took place over circuits set up between Washington and New York on which television over long distances was to be publicly demonstrated eleven days later. It was the culmination of work carried on over several years, and although the end of that particular project, it marked only the beginning of the studies and development that have now led to television networks spanning the entire country.

"In January, 1925, development work had been completed on the system of sending pictures over telephone lines that was to be used in March of that year for the transmission of pictures of the Coolidge inauguration from Washington to New York, Chicago and San Francisco, and soon thereafter to be in commercial service. Today it is in world-wide use by news associations. In discussion with H. D. Arnold, then Director of Research, it was agreed that we should undertake, as our next problem, to speed up the picture system to the point where the product would be television—that is, the production and transmission of a picture in a fifteenth of a second, instead of in seven minutes. At Arnold's request, I prepared and submitted to him on January 23, 1925, a memorandum surveying the problem and proposing a program of research. The survey discussed the characteristic difficulties of securing the requisite sensitiveness of pick-up apparatus; the wide frequency bandwidths which from our experience with picture transmission were indicated as necessary for television; the problem of producing enough modulated light in the received image to make it satisfactorily visible; and the problem of synchronizing apparatus at separated sending and receiving ends. It concluded with the proposal of a very modest attack capable, however, of material expansion as new developments and inventions materialized.

"The apparatus proposed for immediate construction comprised two Nipkow discs mounted at the ends of a single axle, each with a spiral of fifty pinholes. This number was chosen as appropriate to the rendering of the face and shoulders of the subject and on the calculation that the frequency band required for a fifteen-per-second scanning—about ten times that for voice transmission—could be reached on available transmission channels. A photographic transparency, later to be superseded by a motion picture film, was to be used at the sending end, and to secure enough light for the photoelectric cell, it was proposed to focus the crater of a carbon arc lamp on the cell by a lens at the disc plane. At the receiving disc, a crater gaseous glow lamp, modulated by the amplified photoelectric current, was to be imaged on the pupil of the observer's eye. Thus at each end the maximum possible optical efficiency for utilizing the light was insured. . . .

"A memorandum of May 12, 1925 [by a colleague] . . . records: 'I witnessed today a demonstration of Mr. Ives' system of television. He has constructed and put in operation substantially the system he described in his memorandum of January 23, 1925, to Mr. Arnold. In viewing the picture at the receiving end, I could distinguish with fair definition the features of a man's face like that of a picture at the transmitting end and also observed that when the picture at the transmitting end was moved forward or backward, or up and down, the picture at the receiving end followed these motions exactly.' . . .

"A second development at this time was the design of a light source for the receiving end which did away with the original focusing of a point source on the eye. It consisted of a flat-cathode neon glow lamp, with a uniform bright area of glowing gas covering an area as large as the rectangle scanned by the disc. These lamps, which were used in all the subsequent work, permitted direct viewing of the image by both eyes, or even by several observers. The apparatus was no longer a 'peep show.'

"With the two ends separated and with the flat-cathode glow lamps, motion pictures from a projector driven in synchronism with the discs were successfully reproduced in December, 1925. Further work on film was sidetracked by the development of a method of scanning objects without intermediate photographic amplification.

"This beam, or spot, scanning method was devised by Frank Gray. It consists in directing an intense narrow beam of light on the subject and moving the beam rapidly across and from top to bottom of the field in a pattern traced out by the holes of the scanning disc. By this means the average illumination is reduced in the ratio of spot to field size (in our case 2,500 times) so that what would be intolerable as adequate floodlighting becomes almost unnoticeable, but remains equally efficient for scanning purposes. This method, it was found, had been previously proposed, but apparently with no realization of one of its major advantages: that it is not restricted in use to flat surfaces, as originally disclosed, but is suitable for objects in the round. With this method, light source and photocell are reversed in their role, and it is the photocells, not the light source, that should be made larger and manipulated in position. Cells in multiple, of a size never before attempted, were thenceforth used in appropriate positions around the scanned object.

"On March 10, 1926, at the conclusion of ceremonies at Bell Telephone Laboratories commemorating the fiftieth anniversary of the telephone, F. B. Jewett, President, and E. B. Craft, Executive Vice President, were invited to visit the television laboratory. There they talked over the telephone, with the expressions and movements of the face of the speaker being clearly seen by the distant listener.

"Had our conception of the problem been satisfied by the production of image dissecting and recovering apparatus, operable from one room to another, we could have designated and announced this apparatus as 'television.' From the beginning, however, it had been considered a necessary part of our obligation as an enterprise engaged in the transmission of information over great distances, to produce for vision a close parallel to what had been done for voice. It would be television when the laboratory experiment was expanded to cover distances beyond any the eye could reach. Accordingly, consideration was given to the problem of putting the photoelectric signals on practical long-distance communication channels. . . . The frequency range from 15 to 20,000 cycles per second generated by the apparatus had to be put on the transmission medium—wire line or radio—at the proper uniform level, free from phase shift distortions, and delivered with the necessary amplification at the receiving end, a problem of the same sort, but of exaggerated scale, as in picture transmission.

"While this work was under way, attention was turned to a method, outlined early in 1925, of exhibiting the picture to an audience of considerable size—the visual equivalent of a public address system. It employed a long neon tube containing 2,500 separate external electrodes, which was bent back and forth in fifty rows in such a way that there were fifty electrodes in each row. Signals were distributed by a commutator to each electrode in turn, in synchronism with the sending disc. On the grid, 2 by 2½ feet in size, a human face and shoulders were reproduced in the pink glow of the neon gas and of a size and brilliancy sufficient to be seen in a moderate-sized auditorium. With a loudspeaker, it reproduced the voice and sight of the subject before the scanning transmitter.

"In December, 1926, the characteristics of the line coupling apparatus had been worked out, the 'big screen' was functioning, and it appeared possible at an early date to stage a test of actual transmission of vision to a distance. . . . Washington was selected as the far point for the wire demonstration, and the Laboratories' station at Whippany, New Jersey, for the radio demonstration. . . .

"In the log book already quoted, the entry for April 7, 1927, is 'Television demonstrated.' The stage was the Laboratories' auditorium at 463 West Street, which was equipped with apparatus for sending and receiving locally, and for receiving television programs from Washington and Whippany. The principal event was an address by Herbert Hoover, then Secretary of Commerce. As he spoke in Washington, his face was shown on the large screen to a group of fifty guests in New York while his voice was heard from an associated loudspeaker. Following this, a program of amateur vaudeville was sent by radio from Whippany and similarly viewed. Then guests in Washington were individually seen and talked with by friends in New York, using the small individual receiving discs. Local transmission at either end made it possible for all to comprehend the process of image analysis, transmission and recomposition.

"In the years immediately following, a number of developments were announced which together embraced practically all the applications of television that have thus far offered promise of general use. In 1928, the development of large dimension apparatus of great light-gathering power permitted outdoor scenes to be televised by daylight. In 1929, television in color by a three-color, three-channel method was shown. In 1930, a complete two-way telephone-television system was set up between the Laboratories and 195 Broadway. It was maintained for over a year, and was used by more than 10,000 people. While these developments were not ready for exhibition in 1927, they were nevertheless all scheduled and in part worked out then, so that they belong properly in the account of the launching of television at that time.

"In the twenty years that have elapsed since these pioneering developments, the 'head and shoulders' target of the first television scanning have expanded into the extended scene of the stage and arena. For the greater sensitiveness and rendering of detail necessary, electronic scanning methods have superseded the earlier mechanical devices. For the study of the transmission problem, which is the peculiar obligation of the telephone industry, the apparatus of 1927 served well. By its use the fundamental data were obtained which guided in the transition from the open-wire line to the coaxial cable, on which television images were transmitted ten years later in 1937, and from line of sight radio to the radio relay of 1947."

The interest of the Bell System in television was not primarily in devising terminal equipment for home entertainment, but was more importantly in determining requirements which wire and radio transmission would have to meet in the future. For these ends the work of Ives provided necessary tools, and his background of photography and photometry furnished the knowledge needed for going ahead. While the instrumentalities used by Ives in the first long-line transmission of television were far from being adequate for television as we know it today, the fundamental requirements remain the same, and from the experience gained from this first demonstration the transmission engineers of the System were given a sound basis for building transmission circuits that would meet the demands of this new and rapidly growing medium of communication. Notable in this connection was the development of precision measurement techniques to appraise quantitatively the quality of television transmission in relation to the frequency band-width of radio and wire transmission systems. The results of the work of Ives and his associates and followers in Bell Laboratories are evident in the fine performance of today's nationwide television networks.

To one of the questions in the questionnaire already mentioned, Ives replied "I regard my work on the photoelectric effect as probably my most important contribution to science." Apart from a paper published in 1917, this contribution began in 1922 and continued into 1938, so that practically the whole of it was made at Bell Telephone Laboratories.

The photoelectric effect is the emission of electrons from metals irradiated with light. Most metals display it for the ultraviolet only, but the alkali-metal elements and their alloys exhibit it in the visible spectrum, some even into the infra-red. The work of Ives was done upon these. Following what was obviously his wish we treat it here as a contribution to science. Nevertheless its importance to television should be mentioned. The photoelectric current is instantaneous—that is, it starts immediately the light is turned on, and stops immediately the light is turned off; and its strength is rigorously proportional to the intensity of the light.

The photoelectric effect of alkali metals is remarkably complicated, owing largely to its dependence on the polarization of the exciting light. When the light is plane-polarized and is incident at some angle other than 90° (often the experiments are made with light incident at 60°) the emission may be twenty or more times as great when the electric vector of the light is in the plane of incidence than when it is perpendicular to the plane of incidence. In a rather poor but customary terminology (which Ives deprecated) the former is called the *selective* and the latter the *normal* effect. The great difference between the two had been discovered more than thirty years earlier, by German physicists working on liquid sodium-potassium alloy; but it had remained a mystery. Ives undertook to study these effects on thin films of alkali metals, deposited on metals and on glass.

Ives was surprised to discover that these effects, and particularly the ratio *R* of the currents in the selective and the normal effects, were extremely sensitive to the thickness of the film and to the nature of the substrate. Sometimes, as for instance with sodium, he would allow the film to thicken for several hours, and watch the progress of the effects and of the ratio *R* as it thickened. Sometimes, as for instance with potassium, the film would attain its maximum thickness in the course of a few minutes, too rapidly for such a procedure to be used: Ives would then reduce the thickness step by step, by temporary heating while the walls of the tube were held at liquid-air temperatures so that the metal driven away from the electrode would not return to it. In all cases he found that the ratio *R* passed through a maximum, becoming small when the film arrived at its normal thickness. We need not describe his conjectures as to the explanation, since they were destined to be superseded by his later work. It should be mentioned at this point that all these films were invisibly thin.

It thus appeared that alkali metal in bulk would not show the difference between the selective and the normal effect. Yet the difference had been discovered (in 1897) in experiments on a bulk metal, to wit, the equimolecular or 50-50 alloy of sodium and potassium. It is unlikely that Ives mistrusted those results, since they had been confirmed by more than one prominent physicist; but he now proceeded to investigate liquid metals in bulk. Pure sodium and pure potassium showed no remarkable values of *R*. The equimolecular alloy of sodium and potassium did show them; Ives confirmed the results of his forerunners, but he also went beyond. The forerunners had confined their work to the 50-50 alloy. Ives made a numerous series of alloys, ranging in composition from less than 10 percent of sodium to less than 10 percent of potassium. He plotted the ratio *R* against the composition, and again he got a surprising result. The curve showed three extraordinarily high and narrow peaks: one at 18 percent sodium, where R rose to 14; one at the 50-50 alloy, where R was 16:1; one at about 90 percent sodium, where R ascended to no less than 31. It seemed natural to assume that the normal effect was varying monotonically, while the peaks disclosed the variation of the selective effect. This proved not to be true: other experiments showed that each of the two varied in a curious way with composition.

Up to this point, the selective and the normal photoelectric effects had remained as mysterious as ever. Now suddenly Ives conceived a grand idea. The genesis of this idea he traced in his Rumford lecture (1951) back to his doctoral thesis of 1907-1908. We have seen that Ives' thesis pertained to the Lippmann method of color-photography, and it has been explained that the Lippmann process depends upon standing waves formed in a thin emulsion by interference between the incident beam of light and the beam reflected from a specular metallic surface underlying the emulsion. More than twenty years later, Ives guessed that the curiosities of the normal and the selective photo-effects in his thin films of alkali metals might be due to the standing-wave pattern formed in the film by interference between the incident beam and the beam reflected from the specular metallic surface on which the film had been deposited.

This "hunch" was right. To test it, a considerable amount of calculation was required, for the standing-wave pattern depends on the "optical constants" of the underlying metal as well as on the state of polarization and the angle of incidence of the oncoming light, and the dependence is a complicated one. (Incidentally, Ives remeasured the optical constants of sodium, potassium, rubidium and caesium as a contribution to this enterprise.) It then was found that the photoelectric emission, in a wide variety of cases, was proportional to the intensity of the standing waves in the alkali-metal film. Thus was resolved one of the major problems of photoelectricity! This the present writer believes to have been what Ives had mainly in mind when he characterized his work on the photoelectric effect as his most important contribution to science.

We mention another of Ives' many remarkable observations, this pertaining to the long-wave limit of the photoelectric effect. At the long-wave limit the photoelectric emission stops, there being no effect produced by longer waves—that is to say, by photons of lesser energy than the value corresponding to this limit. Ives found that as the thickness of a film is varied, the long-wave limit moves out to the resonance wavelength of the free atom of the element in question, and then moves back. This was demonstrated for each of the five alkali-metal elements Li, Na, K, Rb, and Cs. This is not just a case in which two phenomena move monotonically in the same direction as the atomic number of the element is varied: for Li the resonance wavelength lies *between* those for Na and K, and so does the maximum excursion of the long-wave limit.

Here let us pause to commemorate the principal collaborator of Herbert Ives.

In Bell Telephone Laboratories, with its large professional population and great diversity of technical competence, cooperation is characteristic of almost all undertakings. Just as Ives was able with his own specialized interests and knowledge to advise and help his many associates, so did he gain in return from those around him. It would go beyond the proper scope of this memoir to list all who worked closely with him and for him, but there was one who was so much after his own heart that special mention seems not out of place. This was Edwin F. Kingsbury, who had worked for Ives in the United Gas Improvement Company, was associated with him in the Army in World War I, and followed him into Bell Laboratories. A good scientist on his own account, Kingsbury was the ideal collaborator, the self-effacing companion and aide, who rejoiced in the success of his leader as whole-heartedly as he contributed to it. It is our misfortune as compilers of this chronicle not to be able to include the personal reminiscences of this admirable disciple who died only four months after his mentor.

The last of Ives' major interests in the field of physics bore upon the theory of relativity. It was in 1937 that this topic first appeared among his papers. To the experimental basis of this theory he made very important contributions in collaboration with his colleague G. R. Stilwell. Here we have the great advantage of being able to quote from an analysis of this work made for us by the distinguished physicist H. P. Robertson of the California Institute of Technology, the leading authority in this field. Robertson writes as follows:

"Ives' work in the basic optical field presents a rather curious anomaly, for although he considered that it disproved the special theory of relativity, the fact is that his experimental work offers one of the most valuable supports for this theory, and his numerous theoretical investigations are quite consistent with it.

"His work on the so-called transverse Doppler effect, performed with Stilwell in the period 1938-41, is one of three crucial optical experiments which, taken together, lead inductively to the Lorentz transformations as used in the special theory of relativity; in a sense it, more than either of the other two, may be considered as the cornerstone of the special principle of relativity, as formulated years before by Einstein. The other two experiments—those of Michelson and Morley (1886-), and of Kennedy and Thorndike (1932)—suffice alone only to establish the Lorentz transformations in the form

$$t' = k(v) \quad (t - vx/c^2), \qquad y' = k(v)\, y,$$
$$x' = k(v) \quad (x - vt), \qquad z' = k(v)\, z,$$

where $y = (1 - v^2/c^2)^{-1/2}$ and k(v) is an *unknown* function of the relative velocity v. This form, used by Lorentz himself, predicts only a relative contraction in the direction of motion, as compared with the behavior of matter in the directions transverse thereto. No experiment involving only travel times of light can determine the parameter k(v), which must be unity in the special theory of relativity but can differ from this value on any theory, such as that of

Lorentz, based on the assumption of an aether as a preferred reference frame for classical electromagnetism.

"The Ives-Stilwell experiment, on the second order Doppler effect in light from cathode rays, shows that k is in fact equal to unity within the observational error, in quite direct confirmation of Einstein's special principle of relativity in the optical field. E. T. Whittaker, in his recent *History of Theories of Aether and Electricity* (Vol. 2, p. 42), has this to say about the experiment: 'In 1907 Einstein suggested that it [the transverse Doppler effect] might be observed by examining the light emitted by canal rays in hydrogen, on which J. Stark had published a paper in 1906. Stark's experimental results, however, did not seem to confirm the theoretical formula: and it was not until more than thirty years later that H. E. Ives and G. R. Stilwell succeeded in carrying out this experiment with any degree of success.'

"I have at various times examined with care a number of Ives' theoretical papers attacking Einstein's theory, and leading to apparent alternatives to the Lorentz equations of transformation. Originally I looked for errors in Ives' deductions, for I considered his postulates to be consistent with special relativity, and I did not see how he could otherwise arrive at conclusions so apparently at variance with the relativity theory. To my surprise I found that in each case his deductions were in fact valid, but that his conclusions were only superficially in contradiction with the relativity theory—their intricacy and formidable appearance were due entirely to Ives' insistence on maintaining an aether framework and mode of expression. Ives had, in fact, set up a theory which was completely equivalent in substance to the special theory of relativity. I sincerely admired his ability to carry through these intricate deductions, in spite of the complications caused by his adherence to the notion of a preferred frame tied to the aether—but was never able to convince him that since what he had was in fact indistinguishable in its predictions from the relativity theory within the domain of physics, it was in fact the same theory. My only present concern is that some who have not penetrated to the essence of Ives' theoretical work have seized upon it as overthrowing the special theory of relativity, and have used it as an argument for a return to outmoded and invalid ways of thought." So far as we know, Ives to the end remained faithful to his own interpretation of his experiments, and was not won over to the view expressed in the foregoing quotation.

The story of Ives the scientist would not be complete without taking notice of Ives the inventor. Only a small fraction of scientists, even among those engaged in the practical pursuits of industrial laboratories, are inventors of note. Conversely, the accomplishments of many distinguished inventors fail to gain the acclaim that scientists grant to their own kind. Ives was one of that small lot outstanding in both groups: he was both scientist and inventor. No fewer than one hundred United States patents were issued to him, and in only eight of these were there co-inventors. A hundred patents is a big number as patentable inventions go, and places him high in the fraternity of those who have produced new and useful ideas.

As one would expect, most of Ives' patents are for inventions related to his researches in picture transmission and television. He did not, however, confine his inventing wholly to these areas. One of his side-line inventions of special note was the parallax panoramagram, a device to give three-dimensional viewing of transparencies without requiring special spectacles or other attachments to the viewer.

Another feature of Ives' inventing activity is the long duration of the period during which he was productive of patentable inventions. His first patent was issued in 1914, and others continued to appear up to near the time of his retirement. This is unusual. Inventors are mostly young, and most of them cease to be highly productive of inventions during their later years. Especially is this true if they have administrative responsibilities, as did Ives.

We turn now to Ives' two principal avocations—numismatics and painting. It has already been mentioned that among his childhood activities he listed coin-collecting. This was an occupation of his entire life, and it led him to the Presidency of the American Numismatic Society. Here we ask that Society to speak for us, in the language of the memorial that was spread on the Minutes of its Council a month after the death of Herbert Ives.

"Dr. Herbert Eugene Ives, distinguished in the field of optical physics, lately retired from the Bell Telephone Laboratories and holder of the Medal for Merit for scientific services to the country during World War II, had developed the hobby of coin collecting into a deep and fruitful competence in numismatics. His sudden death on November thirteenth deprived his colleagues of The American Numismatic Society of the wisdom and guidance of an elder statesman whose services had taken a wide variety of forms. Though his catholic taste in beauty led him to collect fine coins of many kinds, he specialized in three classes of gold—the nobles of England, the ducats of Venice and the florins of Florence. Study of these three splendid mediaeval groups led him to study also their contemporary imitations, a field in which his learning was unrivalled. Twice he lectured at the Museum of the Society on these subjects and his two publications, "The Design of the Florentine Florins as an Aid to their Dating" and "Foreign Imitations of the English Noble," were expressions of a research that was at once artistic and historical. To his gifts as a scholar, he added usefulness as an administrator. He served on various committees; he was a member of the Council for twenty years and its President from 1942 to 1946. His gift to the Society of medals awarded to his father for scientific accomplishments caused him to be enrolled as a Patron. But it is as a person rather than as an official that his colleagues will chiefly miss him. He was full of good counsel. He knew when to speak and when to be silent, and his influence was strong for harmony, for generosity and for good sense."

In addition to all of his other proficiencies, Ives was a painter: a capable portrait-painter in oils, perhaps the best combination of painter and optical scientist who ever lived. Of his portraits well over a hundred are extant; to mention just one of them, there is a fine half-length painting of C. J. Davisson, Academician and Nobel laureate, now in the possession of its subject. To treat of him as an artist would be beyond the powers of this writer; but Ives himself would have preferred to be remembered, in this place, as the inventor of the "three-color palette" which he invariably employed. Quotations in the following paragraph are from his Thomas Young oration delivered before the Physical Society (of London) in 1933. To summarize its content: Ives was aware, as are most physicists and some painters, that Thomas Young had shown that all colors may be reproduced by mixing three basic colors, a red, a green, and a blue-violet. What Ives knew and painters generally did not know was that this statement must be amended when applied to pigments, since pigments operate by selective absorption of daylight and not by selective emission. It is indeed theoretically possible to make a pigment of any color by mixing pigments of three basic colors only, but these colors must be what Ives called a "minus-red," a "minus-green," and a "minus-blue"—daylight *minus* these three colors. Now we quote:

"At the time Young published his three-color theory, the great painters of the late eighteenth and early nineteenth century . . . were painting their pictures with a set of pigments or 'palette' which they had inherited from the old masters. The theory involved in this palette was the primitive one of having a permanent reliable coloring material approximating to each color that the artist might want to reproduce. This primitive idea still dominates the artist's palette, for while the mixing of pigments is a common and unavoidable practice in the painting of pictures, the number of pigments in use is still very great. . . . The average artist uses from twelve to twenty—Ingres used twenty-seven. . . . " In principle it is possible to reproduce any color by mixing three basic pigments, together with white as a fourth; but the desired pigments simply did not exist when Ives began his investigations. "On a preliminary survey, the colors called for appeared to be quite far from any available among the standard artists' pigments. Accordingly an extensive search was made, largely by spectro-photometric analysis [here Ives expresses thanks to A. C. Hardy of the Massachusetts Institute of Technology for making the very large number of measurements by means of his photoelectric recording spectro-photometer] in the field of organic dyestuffs. As a result of this search I have been able to select a set of three colors of a high degree of permanence which approximate fairly satisfactorily the ideals above postulated . . . With this palette—extra pale cadmium yellow, Chinese blue, and a phospho-molybdo-tungstic acid lake of Rhodamine 6-G—together with zinc white as the base, I have done a great deal of painting, and some has been done by several artists whom I have been able to interest in the problem. It proves to be adequate to handle the vast majority of colors needed for naturalistic painting." In conclusion Ives points out that with his palette the changing or fading of the pigments, if any there be, will not result in such differential fading as has impaired or destroyed the beauty of many old paintings; and that artists trained in the use of these pigments will have a better understanding of the physics of light and color than do those who use the old-fashioned palette. Ives himself characterizes the three "basic" pigments just named as good but imperfect approximations to the ideals. The writer suspects that after the date of this relatively early lecture, Ives found other pigments somewhat nearer to the ideal than these; but if this is so, his subsequent literature (so far as we have traced it) contains no allusion to them.

Ives retired from Bell Telephone Laboratories on July 31, 1947—his sixty-fifth birthday. The years of his retirement were spent partly in portrait-painting and partly in foreign travel; in the last summer of his life he went to Italy and the Near East. Shortly before retirement he had obtained the prized privilege of membership in the Century Club of New York. He foresaw that he would spend many happy hours there, and he did. He could not foresee that in joining it he was choosing the scene of his death, which occurred within its walls on November 13, 1953. There he was stricken with a heart attack, and passed from life in the most enviable fashion, without illness and in the plenitude of his powers.

This memoir may properly conclude with a listing of his honors and of his survivors.

The following list of his honors is impressive, though it may not be complete. His presidency of the American Numismatic Society proved his prominence in one of his avocations. His eminence in his vocation is proved by his presidency of the Optical Society of America (1924-25). He was Vice-President of the Illuminating Engineering Society in 1912, and President of the Physics Club of Philadelphia in 1917. He was a member of the American Philosophical Society from 1917 and of the National Academy of Sciences from 1933. Honorary doctorates were bestowed upon him by Yale University (1928), Dartmouth College (1928), and the University of Pennsylvania (1929). "Name" lectures that he gave comprised the Lowell Lectures at Boston (1932), the De Forest Lecture at Yale (1932), the Traill-Taylor Memorial Lecture of the Royal Photographic Society (London, 1933). He was Thomas Young Orator of the Physical Society (of London) in 1933, and delivered a lecture at the Fitzgerald Centennial in Dublin (1951). Medals that he received were the John Scott Medal of the City of Philadelphia (1927), three Longstreth Medals of the Franklin Institute (1906, 1914 and 1918), and the Rumford Medal of the American Academy of Arts and Sciences (Boston, 1951). For his service in World War II he received the Medal for Merit, highest civilian award of the United States Government. In addition to being a recipient of medals, Herbert Ives was a donor of them. In memory of his father Frederic Ives, he established (and designed) the Frederic Ives Medal, awarded biennially by the Optical Society of America; Herbert Ives himself was fifth to receive it.

Herbert Ives was married in 1908 to Mabel Lorenz. His three children are Ronald L. Ives, Principal Research Engineer of the Cornell Aeronautical Laboratories at Buffalo; Kenneth Ives, accountant at Wilmette, Illinois; Mrs. Barbara Ives Beyer, instructor in the history of art at the University of Buffalo. His wife and children survive him, together with three grandchildren who are children of Mrs. Beyer.

It is common to speak of great men as having rare vision, using that word in a figurative sense. It can be said in that same way of Herbert Ives, but in a literal sense as well. He had a truly photographic mind and memory, coupled with the ingenuity of an inventor and with the curiosity and desire for ordered understanding that make a scientist. But in a personal way his avocations were fully as significant as his scientific work. How could a man who did so much have also read as widely as he did? Whence came his interest in coins and medals that led to his becoming President of the Numismatic Society? And whence came the urge for painting and especially for portraiture that gave him and his friends such delight? All, so it seems, stemmed from his desire to see and to understand. As he strove in painting portraits to reflect the soul of his subject, so his own soul was reflected in his works and in his life. His was a gentle and kindly soul, not seeking power but exerting it by casting light on things and people around him. To the end he retained the sparkle of youth, while radiating the glow of understanding that comes with maturity.

KEY TO ABBREVIATIONS

Am. Inst. Elec. Eng. Trans. = American Institute of Electrical Engineers, Transactions
Am. Inst. Mech. Eng. = American Institute of Mechanical Engineers
Astrophys. J. = Astrophysical Journal
Bell Syst. Tech. J. = The Bell System Technical Journal
Bull. Bur. Stand. = Bulletin, Bureau of Standards
Eighth Int. Cong. Appl. Chem. = Eighth International Congress of Applied Chemistry
Elec. Rev. = Electrical Review
Elec. World = Electrical World
Illum. Eng. = Illuminating Engineering
J. Eng. Educ. = Journal of Engineering Education
J. Franklin Inst. = Journal of the Franklin Institute
J. Optical Soc. Amer. = Journal of the Optical Society of America
J. Soc. Mot. Pict. Engrs. = Journal of the Society of Motion Picture Engineers
Lighting J. = Lighting Journal
Philos. Mag. = Philosophical Magazine
Photo. J. = Photographic Journal
Phys. Rev. = Physical Review
Phys. Zeits. = Physikalische Zeitschrift
Proc. Am. Acad. Arts Sci. = Proceedings, American Academy of Arts and Sciences
Proc. Am. Philos. Soc. = Proceedings, American Philosophical Society
Proc. Nat. Acad. Sci. = Proceedings, National Academy of Sciences
Proc. Phys. Soc. = Proceedings, Physical Society
Rev. Sci. Instr. = Review of Scientific Instruments
Sci. Mo. = Scientific Monthly
Trans. Am. Electrochem. Soc. = Transactions of the American Electrochemical Society
Trans. Illum. Eng. Soc. = Transactions of the Illuminating Engineering Society
Trans. Soc. Mot. Pict. Engrs. = Transactions of the Society of Motion Picture Engineers
Zeits. wissen. Photogr. = Zeitschrift für Wissenschaftliche Photographie

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1,270,830	Apparatus for and Method of Testing Visual Acuity	1918
1,449,512	High Temperature Measurement	1923
1,494,548	Photometer	1924
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1,545,659	Sheet Mounting Device	1925
1,580,896	Picture Analysis	1926
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1,606,227	Transmission of Pictures by Electricity (with Horton and Long)	1926
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1,656,915	Transmission of Pictures by Electricity	1928
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1,970,936	Photography	1934
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1,987,443	Relief Picture in Natural Colors	1935
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