Inventing Instruments and Users
Harold Edgerton and the General Radio Company, 1932-1970

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In 1932, the General Radio Company of Cambridge, Massachusetts, began selling its first stroboscope, consisting of a portable power unit connected by cable to a mercury-arc flash lamp. A capacitor discharged into the lamp ionized its gas and produced a brief, intense flash of light. The nineteenth-century Geissler tube, discharged intermittently, had become a stroboscopic flash tube.

Listed under the code word "MAGIC" in the company's catalogue, the 1932 GR strobe was capable of generating powerful, short flashes of light (5 microsecs) at precisely timed, variable rates of up to 180 flashes/sec. Over the next three decades, the company would develop and market a series of faster, more portable and relatively inexpensive strobes (see Table 1). Its final models of the 1960s featured xenon-filled flashlamps and solid-state circuitry, with flashes of less than one microsec in duration at rates of up to 2500/sec. A signature product for General Radio, one of the first electronics companies in the United States, the stroboscope by the 1950-60s would become ubiquitous in industrial plants, scientific laboratories and physics classrooms across North America and Europe. Like the air pump in the eighteenth century or the induction coil in the nineteenth, the electronic stroboscope would become one of the iconic scientific instruments of the twentieth century (see Fig. 1).

Other companies in Europe and America would develop and market electronic strobes. Many of the early models, such as the "stroborama" by the Société des recherches mécaniques et physiques in France, the "stroboglow" by Westinghouse, or the "neon-electric stroboscope" by General Electric disappeared from the market by 1935. Later versions, developed after World War II by Philips in Holland, Dawe Instruments Ltd. and EMI Electronics in Great Britain, DISA Elektronik in Denmark, AEG and Frank Früngel in the Federal Republic of Germany or the Communications-Measurement Lab and Electronic Brazing Company in the United States, would find wider and more lasting sales. Although comparative international sales figures would be difficult to assemble, the GR strobes did become increasingly omnipresent through the 1970s. [1]

The success of the GR strobes, although related to that firm's traditionally close ties to its customers and to the acclaimed quality of its products, must also be explained by its relationship to Harold "Doc" Edgerton (1903-90). This MIT electrical engineer, inventor of the early GR stroboscopes and life-long promoter of technology would become an extremely effective salesman for the GR strobes. It is this relationship between a MIT professor and an early electronics company that I wish to examine in this essay. Together, they developed a new instrument and new users for it.[2]

GR had its origins in the Clapp-Eastham Company, a manufacturer of X-ray equipment founded in 1906 that increasingly found itself supplying components, such as induction coils, to amateur radio enthusiasts. As Clapp-Eastham grew and moved to Kendall Square near MIT in Cambridge, Massachusetts, Melville Eastham, himself a radio enthusiast, noticed the lack of measuring instruments for the high frequencies used in radio. With $9000 from three investors, he broke away in 1915 to found GR. Resisting the temptation to build radio transmitters or receivers for the emerging mass market, Eastham kept his fledgling company focused on test equipment. Its goal was to provide off-the-shelf, ready-to-use instruments to research labs or industrial firms. In the words of a later president, GR instruments, "like machine tools … made it possible for customers to concentrate on results, undeflected by the need to cobble up the means of achieving them." GR did not offer electronic apparatus to the general consumer; rather, it sold precision instruments—vacuum tube voltmeters, standard signal generators, sound-level meters, impedance bridges, wave analyzers—to other firms who did supply those markets. [3]

The company remained relatively small, growing from 100 employees in the 1920s to around 1000 employees in the 1960s. Annual sales reached $1 million in the late 1930s and would surpass $20 million in the 1960s. Although by the 1940s the company was offering hundreds of different instruments, stroboscope sales comprised a steady 5 to 6 percent of the firm's sales through the 1950-60s. In the 1950s, GR was selling about 1000 strobe units annually; the number rose to perhaps 4000 units annually by the mid 1960s.[4] Several GR strobe models remain available today, offered by a firm that picked up some of its product lines when GR disaggregated in the 1990s.[5] GR strobes have had long market lives.

GR's first strobe models, in the 1930s, were marketed as "Edgerton Stroboscopes." Unlike most of the company's products, developed in-house with patents owned by company engineers, the strobes were produced under a license from Edgerton (and later from the company of Edgerton, Germeshausen & Grier). The technology emerged from a melding of three venues--the General Electric Company, Department of Electrical Engineering at MIT, and GR, located near the MIT campus. Research problems, technological components, and cultural practices from each venue would find expression in GR's 548 strobe, all orchestrated by the entrepreneurial Edgerton.

Inventing the Instrument

General Electric provided Edgerton with an engineering problem and a new electronic component, the thyratron or gas discharge tube with a control grid. Before entering MIT as a graduate student (he would remain there, finally as Institute Professor, until his death in 1990), Edgerton had spent the 1925-26 year studying synchronous induction motors at the GE Research Laboratory in Schenectady, New York. The problem of how understand and of then how to pull back "into step" these motors under changing loads had a high profile in electrical engineering of the 1920s, presenting difficult puzzles for theory, computation, and measurement. It was in the GE lab that Edgerton later remembered first seeing a stroboscope being used to "freeze" the motion of rapidly rotating motor armatures.[6]

His contacts in Schenectady also provided Edgerton with early access to the thyratron, a gas-discharge tube developed by GE engineer A.W. Hull in 1928. Hull had designed the tube to function as an electronic rectifier or a relay in which a small current applied to a grid triggered the flow of a much larger current. Under certain conditions, the larger current can generate an intense flash as the gas becomes ionized. Although several GE engineers did experiment with a neon thyratron as a flashlamp, in the 1930s the company did not produce flashlamps; indeed they worried initially whether an adequate market existed for the thyratron (one of the first vacuum tubes marketed that had no direct application in radio circuits).[7] Edgerton, however, would turn the thyratron into a mercury flashlamp, and would incorporate other GE thyratrons as triggers into the circuits controlling his stroboscopes.

Edgerton spent the summer of 1929 back at GE, apparently working with the thyratron since he signed an agreement with GE's patent office, reserving the invention of a "stroboscope—a device using an electrical circuit including a mercury-arc lamp, for observing moving objects."[8] In 1930, he sent drawings to GE's Vapor Lamp division, asking whether they could modify one of their thyratrons to make a mercury flashlamp. He wrote a long letter to Hull, describing his work of the past several years on strobes, sending several circuit diagrams, and bemoaning the lack of tube-making facilities at MIT: "I hope that the General Electric Company will be interested enough in this device to furnish me with one or two tubes of special design so that we can develop a real useful research instrument." By May 1931, GE expressed an interest in developing a stroboscope and even tried to hire Edgerton, an offer that he immediately leveraged into an assistant professorship at MIT. Yet in July 1931, Edgerton requested permission use one of GE's thyratrons as the trigger in a stroboscope that he hoped to commercialize elsewhere. For reasons not revealed by the extant correspondence, a collaboration with GE fizzled. Edgerton would turn not to GE but rather to General Radio to build his stroboscope, with the flashlamps manufactured by yet another company.[9] But GE's thyratron did provide Edgerton with the initial design for a mercury-pool flashlamp.

MIT's Department of Electrical Engineering provided the second venue in which Edgerton's stroboscope emerged. In the 1920s under the dynamic influence of Vannevar Bush, this department encouraged its faculty to work on problems of immediate relevance to the electrical industry, to collaborate extensively with commercial firms, and even to create their own private companies. EE students participated in "co-op" educational programs at local firms. That the young Edgerton, who completed his masters and doctoral theses on synchronous motors in 1927 and 1931, respectively, would from the beginning of his MIT career interact with industrial firms and seek to market stroboscopic equipment reflects the ethos of applied engineering that Bush encouraged. Not coincidentally did Edgerton use Bush's newly developed mechanical, analog computing machine, the integraph, to solve the non-linear differential equations required for his thesis work. Not coincidentally did Edgerton write a long report for Bush in December 1931, listing promising scientific and industrial applications for flashlamps and the industrial firms where he already had installed stroboscopic equipment: "Every day or so new applications of this light are brought to my attention. I feel very enthusiastic about the tube and the circuits, and should certainly like to get some one to back me financially, take out patents, and push the business end of the development."[10] From the beginning, Edgerton sought to build stroboscopes for practical applications; the physics of gaseous discharge or theoretical analyses of high-frequency electronic circuits would never become central for his work.

Unfortunately, several of Edgerton's laboratory notebooks, covering his initial stroboscopic work, have not been found.[11] According to later accounts, he once noticed that flashing light pulses, generated by large mercury-arc thyratrons used to rectify current supplying the synchronous motors in MIT's Dynamo Lab, "froze" the rotors turning at the same rate as the alternating current in the thyratrons. By the spring of 1928, Edgerton, always a showman, was demonstrating a "thyratron mercury-arc stroboscope" for the public at open houses of the Department of Electrical Engineering. By the spring of 1930, two MIT masters theses, on a mercury stroboscope and the characteristics of the thyratron, were completed under Edgerton's direction. By that fall, he served his first customer, building a "thyratron stroboscope" for the New England Power Association, and taking it to their hydroelectric facility at Fifteen Mile Falls, Vermont, to measure generator angles. And by December 1930, he took his first "stroboscopic motion pictures" of a synchronous motor pulling into step. Edgerton apparently created a sensation when he showed these movies in January at the convention of the American Institute of Electrical Engineers. From the audience, Bush praised Edgerton's strobe and its "interesting possibilities for further development."[12]

That spring Edgerton published his first descriptions and circuit diagrams of the "mercury arc thyratron" (see Fig. 2). In articles appearing in the journal of the American Institute of Electrical Engineers and in the *Journal of the Society of Motion Picture Engineers*, he described the apparatus used to make the motor movies and reproduced strips of the film (he called them "strobograms") showing slight changes in angular position of the rotor over time. Both articles emphasize the actinic color of the light, making it ideal for photographic film, the short duration of the flashes (10 microsecs) and their intensity. The flashlamp, with a mercury-pool cathode, is only vaguely described. U.S. patent law allowed inventors one year after public disclosure to file and Edgerton would apply for his first patent exactly a year later.[13]

Edgerton's initial articles disclosed few technical details and not to cited no earlier work on strobes, electronic or mechanical. A brief item in the *Scientific American*, published that spring, announced a "new type of stroboscope" developed at MIT, but did not explain wherein its novelty arose. The French stroborama, commercially available since 1928 (a company engineer had demonstrated the device to President Stratton and other potential users at MIT in May of that year!), employed a design quite similar to Edgerton's, discharging a capacitor through a gas discharge tube. But the stroborama used neon tubes, whose yellowish light did not well expose photographic film, and did not place a third terminal in the tube to trigger the discharge. Edgerton's exploitation of the thyratron design was indeed novel, but his published articles emphasized rather the novel applications for his strobe, especially for photography. ".. the main improvements of this stroboscope over others on the market is the possibility of taking still and movie photographs, the excellent visual quality and intensity of the light, the portability, the flexibility, and the simplicity of the tube and the circuit."[14]

After finishing his doctoral dissertation (supervised by Bush) in the spring of 1931, Edgerton immediately began to commercialize his stroboscope. He formed an informal partnership with his student, Kenneth J. Germeshausen, who recently had completed his B.S. thesis on synchronous motors, to build custom-designed strobes for industrial customers. They acquired glassblowing equipment and started experimenting with flashlamps and circuit design; by November they moved into their own laboratory space. At MIT, word quickly spread about the strobes and MIT faculty began to borrow or purchase apparatus from Edgerton. C. Stark Draper of the Department of Aeronautical Engineering, for example, sought Edgerton's help to photograph the dynamical behavior of aircraft engines and propellers running at full tilt. And given the many ties between MIT faculty and industry, outside interest began to develop. Electrical power generating companies, local industrial plants with rapidly moving machines, printing companies, Arthur D. Little's consulting company, and the Sperry Gyroscope Company provided the first orders even before Edgerton initiated the collaboration with GR.[15]

Stroboscopic motion pictures would be the problem that brought together the General Radio Company and Edgerton's, creating the third venue for the innovation. From the beginning, Edgerton had wanted to make not only single-flash photos or multi-flash exposures on a single negative but moving pictures that could be played back at reduced speeds to "slow down" rapid phenomena. His initial motor movies were made with a traditional movie camera. From Draper he had borrowed a high-speed movie camera, but both employed mechanical shutters to expose individual frames on the moving film. If stroboscopic illumination is intense enough, however, a shutter is not necessary. One can simply hold the shutter open and expose the moving film by the successive flashes. At hundreds of flashes per second, however, the film must move very rapidly through the camera.

In 1928 GR had developed a string oscillograph, a rather awkward mechanical device that enabled users to observe a rapidly oscillating voltage by projecting the shadow of a vibrating tungsten wire onto a time axis supplied by a rotating octagonal mirror. In 1931, GR's first full-time engineer (hired in the early 1920s), Horatio W. Lamson, MIT '15, Harvard AM '17, fitted a shutterless, continuous-film camera to the oscillograph. Hand-cranked or motor-driven sprockets pulled the film behind of the string's shadow, recording traces of the oscillating voltage. A year earlier, another GR engineer, James K. Clapp, MIT '23, had developed a "stroboscopic frequency meter" for calibration work within the company. In this device, the unknown frequency drove a neon flashlamp which illuminated a specially marked disk rotating at a known frequency. Both instruments intersected with Edgerton's interests.[16]

On 17 September 1931 Edgerton recorded in his lab notebook: "Spent several hours at the General Radio Company with J.K. Clapp (Eastman?) (Folsum?). They were all very interested in the stroboscopic movies of the valve mechanism. I had a print of several frames showing a compression wave as it traveled back and forth through the spring.

They plan to come over next week … to see the apparatus." This was probably Edgerton's first visit to the Cambridge firm, for he appears to not remember all the people he met. Clapp did attend Edgerton's next "stroboscopic display" in MIT's Dynamo Lab. And in December, Lamson brought the GR camera to Edgerton's lab where they took stroboscopic moving pictures of a synchronous motor, vibrating springs, and the behavior of the cathode "hot spot" in a mercury thyratron. Apparently, both parties were mutually impressed. On 30 December, Edgerton noted: "Lamson of the General Radio Company called up by phone in the morning and asked me to come over to talk with them regarding the stroboscope. We had a long talk with Mr. Horton who believes the strobe will be a useful device now that it has enough light to take pictures."[17] J. Warren Horton, MIT '14, had joined GR as "chief engineer" in 1928. By January 1932 he was seeking a tube company to make flashlamps. In June, he signed an agreement with Edgerton, whereby GR would manufacture and sell mercury-arc stroboscopes of Edgerton's design (the 548) in exchange for a royalty and for continued engineering aid from Edgerton and Germeshausen. Several years later, these two would redesign the 548 for an argon cold-cathode flashlamp and the royalty would be set to fifteen percent of the retail sale price. The royalty on the 631 strobotac, introduced in 1935, was $6 of the retail price of $93. Although MIT under its new president Karl Compton was in the midst of changing its intellectual property rules in the early 1930s so that individual professors no longer could hold patents on work developed in MIT labs, Bush allowed Edgerton to retain his strobe patents to support the agreement with GR.[18]

Edgerton's lab notebook is missing for the period in 1932 when he and Germeshausen worked with GR engineers to design the 548 "Edgerton Stroboscope." Subsequent lab notebooks illustrate close interactions between Edgerton and GR, up through the 1970s. Edgerton would design circuits, GR would build prototypes, Germeshausen would build flashlamps and test the prototypes, rewire the circuits and take the revised prototype back to GR for further testing. Germeshausen and Edgerton designed a cold-cathode neon flashlamp for the 631 strobe and in the late 1950s a xenon flashlamp for the 1531 Strobotac. They also would advise on quality control and negotiate with tube-manufacturers, such as Hygrade Lamp Company, Raytheon and Sylvania, whom GR variously commissioned to produce flashlamps under GR's name.[19] When in 1963 GR published a *Handbook of high-speed photography* to accompany the new 1531, Edgerton wrote the forward.

The Edgerton strobes were something of an anomaly for General Radio. With only a few exceptions, their instruments were made for testing circuits in radio and communications equipment. And they generally designed their products in-house, with standard components and minimal use of outside patents. GR's relationship with Edgerton was uncharacteristic. On the other hand, GR had always cultivated intimate ties with MIT. During the firm's early decades, fully one-fifth of the employees had college degrees, many from MIT's department of electrical engineering. Seeking to promote close interactions between that department and his engineers, GR president Eastham had even connected GR's phone system into MIT's switchboard. Later in the 1930s, Eastham created a coop program between his company and MIT's Department of Electrical Engineering. Over the years, dozens of these MIT-coops took up permanent employment at GR. It is not coincidental that nearly all of the GR engineers who worked with Edgerton to develop the company's stroboscopes had MIT degrees (see Table 1).[20]

Inventing the Users

"A good idea without a salesman very often doesn't get anywhere." So did Herbert Grier describe Edgerton's role in the informal partnership that after the war became the major consulting firm and defense contractor of EG&G (Edgerton, Germeshausen and Grier).[21] Edgerton did much more than design the strobes produced and sold by General Radio. He would become popularly known as the photographer who could "stop time" with his high-speed cameras and flash equipment. Edgerton made visible "things the eye of man has never seen," gushed a trade newsletter already in 1936. Edgerton's photographs--freezing hummingbirds in mid flight, bullets puncturing apples, rotating fan blades, swinging golf-clubs and tennis rackets, splashing milk, even exploding atomic bombs--both astonished and delighted viewers. In 1937, the first major exhibit of photography at New York's Museum of Modern Art included an Edgerton milk-drop photograph. John Zarkowski, later curator of photography at that museum, once noted that Edgerton's photographs had "hung on our museum's walls almost as consistently as have Picasso's [paintings]." Associated by art historians with the traditions of Muybridge, Marey, Eakins, Futurism and even the Neue Sachlichkeit, Edgerton's photographs clearly resonate with modernist aesthetics, which might explain his popularity in fine-arts circles. Edgerton always presented himself otherwise: "Don't make me out to be an artist. I am an engineer. I am after the facts, only the facts." But Edgerton was not merely an engineer. Not unlike Galileo, Benjamin Martin, or Rudolph Koenig (to name only a few), Edgerton was also a consummate showman. With General Radio's help, he made the stroboscope into a widely used tool for science and engineering, industry, education, and high-speed photography. Edgerton and GR created not only a new technology but also new sets of users for that technology. Together they mounted campaigns to take the strobe beyond the factory. [22]

Industrial users did provide initial sales for both Edgerton and GR. As noted above, even before the GR 548, Edgerton had sold strobes to various industrial customers. These early units were custom designed by Edgerton and Germeshausen and built by the Delta Manufacturing Company, an innovative maker of radio equipment in Cambridge, founded by a former GR foreman, Ashley Zwicker. By 1933 Edgerton was nearly doubling his annual $3000 MIT salary with revenue from these sales.[23]

Similarly, GR began marketing the 548 Edgerton Stroboscope primarily to industrial users. Machine manufacturers, textile mills, chemical and rubber companies, electrical manufacturers, electric power companies, instrument companies, clock makers, automotive and internal combustion engine makers, refrigeration and air conditioning manufacturers, and makers of cameras and projectors purchased most of GR's strobes during the 1930s. University sales remained low. By 1938, only about 30 General Radio strobes had been sold to universities (about ten percent of total sales). Only four had gone to research laboratories (Bell Telephone, Naval Research Laboratories, Physicists Research Company and Hazeltine Services Company). [24]

Yet Edgerton also envisioned the strobe being used many areas of science and engineering. His 1931 announcement of the motor movies appeared in an electrical engineering journal. Over the next year, he pitched the strobe in the journal of the Society of Motion Picture Engineers, *Electronics*, the *Review of Scientific Instruments*, a journal of chemical engineering, and the *American Golfer*. Bearing titles such as "the stroboscope and high-speed motion picture camera as research instruments," these early articles listed dozens of non-industrial uses for the strobes. Chemists could study bubble formation, plastic deformation and rupture of solids, and the motions of their high-speed machines like centrifuges. Physicists might measure linear and angular velocities, illuminate the Wilson cloud chamber, and study the Faraday Effect. Zoologists could analyze the movement of cilia and wings. Golfers could learn that their clubs transfer momentum to the ball entirely at impact and not in the follow-through.[25]

For the next thirty years, Edgerton's MIT laboratory became a center of interdisciplinary research. Collaborating with scientists and engineers from a host of disciplines, he championed stroboscopy as a research tool. Working with zoologists, Edgerton photographed flying fish and swimming sea horses. Working with physiologists, he photographed humans sneezing and vibrating vocal cords. Working with ceramics experts, he photographed the propagation of cracks in glass. Working with the U.S. Army, he photographed areas around Normandy before the D-Day invasion. Working with the French underwater explorer Jacques Cousteau, he photographed the sea floor (his attempts to capture the Loch Ness monster on film were less successful). Many of these articles opened new research fronts that others would explore. By 1950, the strobe would become a standard instrument in laboratories across many of the scientific and engineering disciplines, due largely to Edgerton's energy and GR's inexpensive instruments.

"I put on a show Friday evening in the lab," wrote Edgerton in his lab notebook in December 1930, after having shot his first motor movies.[26] It would be not because research articles or the industrial sales but rather Edgerton's numerous lecture-demonstrations and published photographs that would make the stroboscope so ubiquitous by 1950. Many of Edgerton's photographs contributed little new knowledge to science or engineering. Rather they delighted and even comforted viewers by making previously invisible phenomena seem both understandable and beautiful. By often including portraits of himself making the high-speed photographs, Edgerton further demystified the stroboscopic technology (see Fig. 3). Such reflexive images elucidated for viewers both high-speed phenomena and the means of their capture.

Already in 1932, Edgerton published his first photos of the milk drop splash, both in a technical journal and in MIT's popular magazine, *Technology Review*. In that same year, his first photo of a smashed golf ball appeared in the *Boston Herald*, along with a self-portrait of Edgerton, Germeshausen and their high-speed camera. In August 1932, a colleague from GE urged Edgerton to photograph the motion of a bee's wing or a cricket making its noise. "In this way, I should think you could secure quite a lot of publicity, which might turn up a considerable non-technical demand." Edgerton's 6000 exposure/sec photographs of a house fly appeared next year; his photographs of hovering hummingbirds would appear in the *National Geographic*. At the 1933 Century of Progress Exposition in Chicago, Edgerton demonstrated his stroboscope. Inviting MIT's football coach into his lab, Edgerton photographed a football being kicked, beginning a long line of sports photographs that he would orchestrate. He worked with the GE engineer turned photographer Gjon Mili, whose stroboscopic photographs would appear in *Life* magazine. In 1937, Edgerton would lecture to audiences of 1800 at the Royal Canadian Institute in Toronto, 2000 at the Horace Bushnell House in Hartford, and 4000 for the National Geographical Society at Constitution Hall in Washington. In 1939, Edgerton published his most dramatic photographs, mostly of everyday phenomena of little importance to scientific research, in a critically acclaimed book entitled *Flash! Seeing the Unseen by Ultra High-Speed Photography* (see Fig. 4). In 1940, a ten-minute MGM film showing Edgerton at work, smashing teacups and photographing rattlesnakes and falling cats, won the Oscar for the best one-reel short film. In less than a decade, Edgerton, who would work with Kodak and EG&G to develop electronic flash units for photographers, had turned a scientific instrument into a widely known technology.[27]

Not surprisingly, Edgerton realized that strobes could dramatically display the phenomena of motion in physics textbooks and classrooms. Working with his colleague, Francis Sears, MIT '20 and physics professor there, Edgerton made multiflash photographs of objects in free fall, parabolic motion, colliding on frictionless air-tables, etc., that from 1938 on would grace Sears' legendary physics textbooks, editions of which are still in print. The post-Sputnik physics textbook designed to boost the level of physics instruction in American high schools featured an Edgerton photograph on its cover and described in detail how such images were made (see Fig. 5). Masters theses were written at Departments of Education, exploring how strobes could be used in elementary physics laboratories; one 1975 thesis featured a photograph of the GR 1531 Strobotac on its cover.[28]

GR's inexpensive strobes of the 1960-70s would find their primary use in America's science classrooms. When he lectured at colleges and universities, Edgerton often donated GR apparatus to his hosts. Even after GR cracked down and forced Edgerton personally to cover half the cost of each unit he gave away, the enthusiastic promoter could not curb his generosity. In 1964, he proposed giving a GR 1531 to every electrical engineering department in the country (159 schools), prompting his partner Grier to ask where the $60,000 would be coming from to cover such an expenditure.[29] The last strobe GR would develop, the inexpensive 1542, was aimed explicitly at high school classrooms.[30]

Like the air pump in the eighteenth century or the induction coil in the nineteenth, the strobes made by GR and promoted by Edgerton offered twentieth-century audiences theatrical demonstrations of phenomena not otherwise accessible to everyday experience. An instrument initially developed in MIT's Dynamo Laboratory for industrial use moved from the factory to research laboratories across the scientific disciplines, to physics classrooms in high schools and universities, to photographers' and Hollywood studios and mass-marketed cameras. General Radio and Edgerton not only developed a new scientific instrument; they also created a broad array of users for the apparatus.

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Table 1: General Radio Stroboscopes[31]

Date	GR Type	Name	Initial Price	Flashes per sec	Duration microsec	GR Developer
1932	548	Edgerton Stroboscope	$290	10-180	5-10	H.W. Lamson, MIT '15, Harvard A.M. '17
1933	521	Edgerton Power Stroboscope[32]	1200	10-240		C.T. Burke, MIT '23
1935	631	Strobotac	93	10-240	5-10	H.H. Scott, MIT '30
1939	648	Strobolux	175	20-100	10-15	C.E. Worthen, MIT '28
1945	1530	Microflash	525	Single	2	
1949	1532	Strobolume	225	2-50	10	W.R. Saylor, MIT '36
1960	1531	Strobotac	260	2-420	0.8	M.J. Fitzmorris, MIT '50 M.C. Holtje, MIT '49
1965	1538	Electronic Strobotac	465	2-2500	0.5-3.0	M.C. Holtje, MIT '49
1970	1542	Stroboscope	99	3-63	5	C.E. Miller, MIT '66

Figure Captions

Fig. 1: Emphasizing portability. From General Radio brochure for the Type 631 Strobotac, circa 1938, cover. Courtesy of the General Radio Historical Society.

Fig. 2: Edgerton's first published circuit for the mercury-pool thyratron flashlamp. From HEE, "The mercury arc as a source of intermittent light," *Journal of the Society of Motion Picture Engineers* 16 (1931): 736.

Fig. 3: Edgerton at work, a reflexive portrait. From HEE and C.M. Breder, Jr., "High speed photographs of flying fishes at night," *Zoologica* 26 (1941): plate 1.

Fig 4: Strobograms become art. From HEE and James R. Killian, *Flash!* (Boston 1939), dust jacket.

Fig. 5: Teaching physics for America's high schools. From Physical Sciences Study Committee, *Physics* (Boston, 1960), front cover.

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Endnotes

[1] Laurent Seguin and Augustin Seguin, "Le Stroborama, Nouvel appareil Stroboscopique à Grand Éclairage, Ses Applications Industrielles," *Bulletin de l'Association des ingenieurs-electriciens sortis de l'Institut électrotechnique Montefiore* 10 (1928): 137-56; E.E. Steinert, "Neon-Electric Stroboscope," *General Electric Review* 31 (1928): 136-39; W. Endres Bahls and D.D. Knowles, "The Stroboglow," *Electric Journal* 28 (1931): 250-53; S.L. de Bruin, "An Apparatus for Stroboscopic Observation," *Philips Technical Review* 8.1 (1946): 25-32; Gilbert Kivenson, *Industrial Stroboscopy* (New York: Hayden Book Company, Inc., 1965); Jerzy Rutkowski, *Stroboscopes for Industry and Research [1961]*, trans. Eugene Lepa (New York: Pergamon Press, 1966); Pierre Bron and Philip L. Condax, *The Photographic Flash: A Concise Illustrated History* (Allschwil, Switzerland: Bron Elektronik AG, 1998).

[2] For other studies of technology users, see Nelly Oudshoorn and Trevor Pinch, eds., *How Users Matter: The Co-Construction of Users and Technologies* (Cambridge: MIT Press, 2003).

[3] Donald B. Sinclair, *The General Radio Company, 1915-1965* (New York: Newcomen Society in North America, 1965) 20.

[4] Arthur R. Thiessen, *A History of the General Radio Company* (West Concord, Massachusetts: General Radio Company, 1965). Stroboscope orders for 1954 to 1966, listed as total annual sales in dollars in archival materials held by the General Radio Historical Society, were made available to the author by Fred Van Veen, October 2005. To estimate the number of strobes sold, I assume an average unit price of $300 for those years.

[5] Type 1531 and 1538 Strobotacs are available from IET Labs of Westbury, New York. See www.ietlabs.com/Genrad/index.html (accessed 15 January 2006).

[6] In a 1975 oral interview, HEE mentioned having seen strobes in the GE laboratory; no extant documentary materials confirm this claim. See *Seeing the Unseen: Dr. Harold Edgerton and the Wonders of Strobe Alley*, (Rochester: George Eastman House, 1994) 79ff. I know of no commercially made strobes that would have been available in 1925-26. But contemporary engineers in Europe and America were studying synchronous motors stroboscopically, using light beams interrupted by vibrating strings or rotating slotted disks and neon lamps flashed at standard line frequencies. See Amedeé Guillet, "Mesure Rapide et Précise de la Fréquence de Rotation de L'arbre d'un Moteur Par la Méthode Stroboscopique," *Comptes rendues* 172 (1923): 1447-49; Laurent Seguin and Augustin Seguin, "Sur Un Nouvel appareil Stroboscopique à Grand Éclairage," *Comptes rendues* 181 (1925): 139-41; W.E. Meserve and D. Ramadanoff, "A Simple Method for Determining Slip of Induction Motors and Torque-Angle of Synchronous Motors by Means of a Neon Lamp," *Sibley Journal of Engineering* 41 (1927): 172-74; Steinert, "Neon-Electric Stroboscope," 136-39.

[7] C.G. Found to HEE, 6 March 1931, HEE Papers, MC-25, Institute Archives and Special Collections, MIT Libraries (hereafter cited as MC-25), 70:2; A.W. Hull, "Gas-Filled Thermionic Tubes," *Transactions of the American Institute of Electrical Engineers* 47 (1928): 753-63; W.C. White, "The Story of Electronics Development at the General Electric Company," 1955, t.s., Schenectady, New York, XH2-XH4.

[8] HEE, "Summary of records and dates of work done on the mercury-arc stroboscope," 26 October 1931, MC-25, 70:2. According to this document, HEE in June, 1929 gave "to the GE Patent Dept at their request" the one page of circuit diagrams from his now missing T-1 laboratory notebook. To the best of my knowledge, GE's only strobe patent, for a simple neon flashtube powered by a specially designed transformer, was filed on 19 May 1927 and granted on 10 Sept 1929 to Clifford A. Nickle (US patent 1,728,003).
[9] See Karl Compton to HEE, 1 May 1931, and various letters between HEE and GE engineers, including A.W. Hull, 1930-31, in MC-25, 70:2.
[10] HEE to Vannevar Bush, 9 December 1931, MC-25, 702; W.V. Lyon and Harold E. Edgerton, "Transient Torque-Angle Characteristics of Synchronous Motors," *Transactions of the American Institute of Electrical Engineers* 49 (1930): 686-99; Karl L. Wildes and Nilo A. Lindgren, *A Century of Electrical Engineering and Computer Science at Mit, 1882-1982* (Cambridge: MIT Press, 1985); W. Bernard Carlson, "Academic Entrepreneurship and Engineering Education: Dugald C. Jackson and the Mit-Ge Cooperative Engineering Course, 1907-1932," *Technology and Culture* 29 (1988): 536-67; Christophe Lecuyer, "The Making of a Science Based Technological University: Karl Compton, James Killian, and the Reform of Mit, 1930-1957," *Historical Studies in the Physical and Biological Sciences* 23 (1992): 153-80; G. Pascal Zachary, *Endless Frontier: Vannevar Bush, Engineer of the American Century* (Cambridge: MIT Press, 1997).
[11] MC-25 has lab notebook S[ynchronous machines]-3 (Feb 1930 – Jun 1931) and T[hyratron]-2 (Jul 1931 – Jan 1932). Notebooks S-1, S-2, T-1 (May 1929 – Jun 1931), and T-3 are missing. T-4 begins in June 1933 and is followed by a consecutively sequence of notebooks, documenting without gaps the remainder of HEE's career. MC-25 also has an untitled lab notebook by Germeshausen (Oct 1931 – Jan 1932).
[12] HEE, "Summary of records and dates"; Harold E. Edgerton and James R. Killian, Jr., *Moments of Vision: The Stroboscopic Revolution in Photography* (Cambridge: MIT Press, 1979) 3; Kenneth D. Beardsley, "Development of a Mercury Arc Stroboscope," M.S., MIT, 1930; John M. Kurkjian, "Operating Characteristics of a Thyratron," B.S., MIT, 1930; Harold E. Edgerton and Paul Fourmarier, "The Pulling into Step of a Salient-Pole Synchronous Motor," *Transactions of the American Institute of Electrical Engineers* 50 (1931): 780. MC-25, lab notebook S-3, 50.
[13] Harold E. Edgerton, "Stroboscopic Moving Pictures," *Electrical engineering* 50 (1931): 327-29; Harold E. Edgerton, "The Mercury Arc as a Source of Intermittent Light," *Journal of the Society of Motion Picture Engineers* 16 (1931): 735-41. US patent 2,181,879, filed on 9 May 1932.
[14] F.D. McHugh, "A New 'Whirling Watcher'," *Scientific American* 144 (1931): 262. H. Billioque to S.W. Stratton, 7 May 1928, HEE to H.A. Sherman, 17 Aug 1931, both in MC-25, 70:2.
[15] HEE kept these early business records in his lab notebooks S-3 and T-2. See additional financial records in MC-25, 70:2, 87:5, 89:17, 155:8.
[16] *Catalogue of Laboratory Apparatus*, (Cambridge: General Radio Co., 1928) 107-12. *General Radio Experimenter* 3 (April 1929), 1-4; 5 (Nov 1930), 5-7; 5 (April 1931), 1-4.
[17] MC-25, lab notebook T-2, 45-46, 50, 100, 105, 107.

[18] HEE to Harry I. Day, 1 June 1932, MC-25, 70:2: "I have made an agreement with the General Radio Company to make and market the stroboscopic apparatus that I have developed. A visual type is to be made first, and then we are planning to perfect the motion-picture outfit to go up to 5000 a second." See MC-25, lab notebook T-2, 111; T-5, 61-76; Wildes and Lindgren, *Electrical Engineering* 148.
[19] See MC-25, lab notebooks, T5-T8; MC-25 19:4; 70:4; K.J. Germeshausen, "A Cold-Cathode Arc-Discharge Tube," *Electrical Engineering* 55 (1936): 790-94, 809; Harold E. Edgerton and Pierre Y. Cathou, "Xenon Flash Tube of Small Size," *Review of Scientific Instruments* 27 (1956): 821-25.
[20] Eastman was a member of MIT's Visiting Committee from 1936-39. He donated company stock to MIT, which in the 1960s GR bought back through donations of instruments to various MIT laboratories, including HEE's. See Thurston to HEE, 7 Mar 1968, MC-25, 19:5 and Thiessen, *General Radio* 22. For biographical accounts of GR's early engineers, see "We Celebrate a Birthday," *General Radio Experimenter* 5.1 (1930): 1-20.
[21] Herbert Grier to Gordon Brown, 19 April 1972, MC-25, 20:9.
[22] *The Ashlar* 7 (November 1936), 2-3, 8, in MC-25, 5:1; quotes from Harold E. Edgerton, Estelle Jussim and Gus Kayafas, *Stopping Time: The Photographs of Harold Edgerton* (New York: H.N. Abrams, 1987) 12, 18. A comprehensive biography of HEE remains to be written. See,, most recently, J. Kim Vandiver and Pagan Kennedy, "Harold Eugene Edgerton (1903-1990)," *Biographical Memoirs of the National Academy of Sciences* 86 (2005): 1-23.
[23] MC-25, lab notebook T2, *passim*; HEE federal income tax returns, 1931-33, 1935, MC-25, 155:8; Thiessen, *General Radio* 12; Otto J. Scott, *The Creative Ordeal: The Story of Raytheon* (New York: Atheneum, 1974) 62, 68-69. The earliest published photograph of Edgerton's stroboscopic motion-picture unit featured GR's high-speed camera and a "strobograph" made by Delta Manufacturing. See Harold E. Edgerton and K.J. Germeshausen, "Stroboscopic Photography," *Electronics* 5 (1932): 221.
[24] Undated GR brochure, "Going at top speed," in MC-25, 5:4; "Type 548-A Edgerton Stroboscope," sales data, MC-25, 70:2. In its catalogues, GR always placed the strobes in the sparce section entitled "Industrial Devices." Edgerton later remembered driving with his wife in 1933 back to Nebraska, his home state, taking along one of the first GR 548 strobes, trying to drum up sales at factories along the way. Vandiver and Kennedy, "Edgerton," 4-5.
[25] For a fairly complete bibliography of HEE's publications, see Edgerton, Jussim and Kayafas, *Stopping Time* 162-67.
[26] MC-25, lab notebook S3, 50.
[27] Harold E. Edgerton and Kenneth J. Germeshausen, "The Mercury Arc as an Actinic Stroboscopic Light Source," *Review of Scientific Instruments* 3 (1932): 541; "Photographs at 1-500,000 of a Second Made Possible by Mit Flash Device," *Boston Herald* 14 Oct 1932; Harold E. Edgerton, *Electronic Flash, Strobe* (New York: McGraw-Hill Book Company, 1970) 126-27.P.L. Alger to HEE, 17 Aug 1932, MC-25, 70:2; President's Office to HEE, 1 Dec 1933, MC-25, 70:2; MC-25, lab notebooks T7, 138ff;

T8, 72, 77, 131; *Life*, 25 Dec 1938, 2, 24-25; Gjon Mili, *Photographs & Recollections* (Boston: New York Graphic Society, 1980).

[28] John A. Clark, Frederick Russell Gorton and Francis W. Sears, *Physics of Today* (Boston: Houghton Mifflin, 1938); Francis W. Sears and Mark W. Zemansky, *University Physics*, 4d ed. (Reading, Massachusetts: Addison-Wesley, 1970); Physical Science Study Committee, *Physics* (Boston: D.C. Heath and Company, 1960); Robert William Force, "The Stroboscope and its Use in Demonstration and Laboratory Work in Elementary Physics," M.S., University of Utah, 1965; Carl R. Stannard, John P. Ouderkirk and Bruce B. Marsh, *The Stroboscope: A Module on Forces and Motion* (New York: McGraw-Hill Book Company, 1975).

[29] HEE to Thurston, 15 Jun 1964; Grier to HEE, 24 Jun 1964, MC-25, 19:4.

[30] For HEE's extensive correspondence with GR concerning these promotional activities, see M-25 19:4-5. For GR's relationship with the Center for Educational Apparatus and Physics in New York, see William R. Thurston to F.E. Christensen, 21 Apr 1964, MC 25 19:4.

[31] *General Radio Experimenter*, Dec 1932; Aug-Sep 1933; Aug 1935; May 1939; May 1949; September 1960; April 1966; October-December 1970; *Catalogue K*, 4th ed. (Cambridge: General Radio Company, 1945); *Catalogue S*, (West Concord: General Radio Company, 1965).. By GR tradition, the lead engineer for new product would author the announcement in the *Experimenter*.

[32] The 521 and its successor 621 (announced in *General Radio Experimenter*, April 1935) were sold as one-off instruments, designed to suit individual customers' needs and providing considerably more illumination by employing larger of multiple flashlamps.