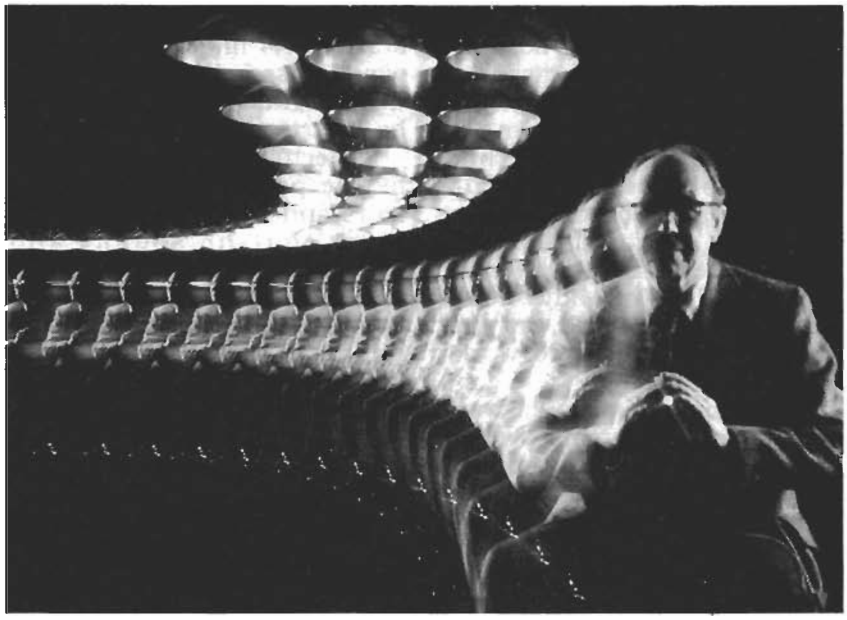
Harold Edgerton was a prolific inventor of stroboscopes, high-intensity lamps, underwater cameras, and specialized sonar. But he is best remembered for his ultra-high-speed photographs that are recognized as works of art.



SEEING the UNSEEN

PHILIP CONDAX

AN EXHIBITION AT THE GEORGE Eastman House in Rochester, N.Y. entitled *Seeing the Unseen: Dr. Harold E. Edgerton and the Wonders of Strobe Alley,* offers the public an opportunity to appreciate some of the outstanding contributions to science, engineering and art made by Dr. Edgerton. The exhibit is scheduled to leave Rochester on October 31 to tour five other museums before it ends in San Diego in 1997.

Photography was only one of the many consuming interests of this American engineer, scientist, inventor, and educator whose curiosity and energy led him to improve large synchronous motors and invent high-intensity flashlamps, stroboscopes, special undersea cameras, and exploratory sonar. This Massachusetts Institute of Technology professor, who died in 1990, actually became an artist by accident.

Dr. Edgerton's perfection of the stroboscope made it possible for engineers to stop the action of moving machines so they could see their faults and correct them, and his methods for "freezing" actions on film that are too fast to be seen by the human eye gave us our first clear pictures of events in the microsecond domain.

While Harold Edgerton might not be a household name, there can scarcely be a person on this planet who has not seen his photographs of a crown formed by a milk drop as it splashes into a saucer or speeding bullets passing through apples and playing cards. Perhaps less memorable, but of great importance to athletes, trainers, and physiologists are Edgerton's multiple-image pictures of a diver's trajectory as he springs off a platform or the fan-like images made by a golf club as the golfer swings to drive a ball.

Edgerton's methods for making those landmark pictures have long since been adopted by others for photographing eggs dropping, birds in flight, and glass bulbs exploding— to mention but a few of his subjects. His techniques advanced man's knowledge of ultra-high speed motions that occur in nature, science, and engineering. But you have probably also seen those television commercials extolling the benefits of stain-free carpet on floors that have received a cascade of slow-motion food spills. All of those special effects owe a debt to Dr. Edgerton's techniques.

Edgerton's early stop-action photographs were taken, almost reluctantly, from his laboratory to art museums where they are now declared to be images of esthetic beauty. His pioneering work on stroboscopes turned a laboratory curiosity into a practical engineering tool for diagnosing faults in moving machines from electric motors to jet engines, and his flashtubes have become standard equipment in the camera bags of photographers.

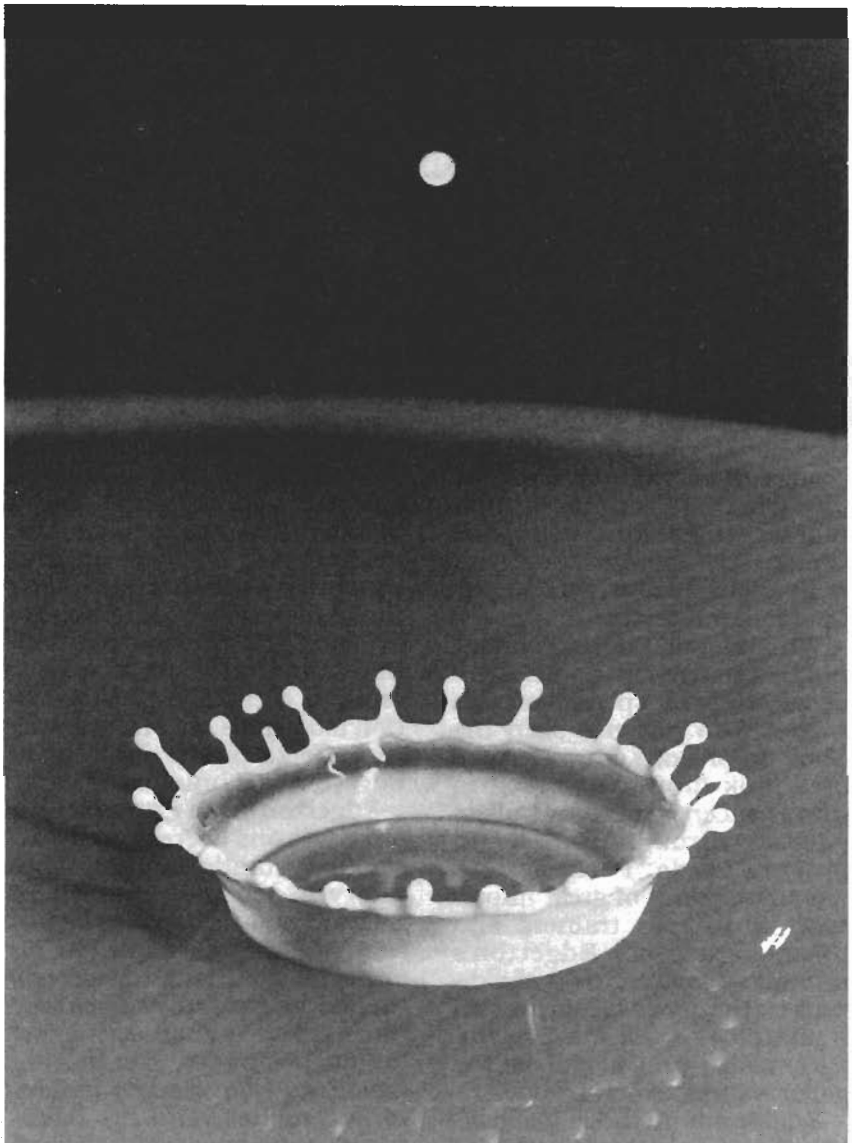
Home on the plains

Harold Edgerton was born in one small town in Nebraska in 1903, but his family soon moved to another small Nebraska town, Aurora. This move was to have a lasting influence on his philosophy of life and career direction. He credited his successes, in part, to being raised on the Midwestern plains where he learned, early in life, the virtues of hard work and perseverance.

But, of more importance was the power station in this town of less than 4000 people. Aurora was one of the few small towns in Nebraska to be electrified before World War I because wealthy farmers living nearby could finance and support a power station. As many as 20 years would pass before many of the neighboring rural towns would be electrified.

Edgerton was so fascinated by the power station's generators and transmission equipment that he sought and obtained work there as a janitor and general laborer while attending high school and during college vacations. As luck would have it, a labor shortage during World War I gave him the opportunity to become a lineman, a prestigious occupation, at an early age.

Not surprisingly, that satisfying work experience determined his major at the University of Nebraska—electrical engineering. While still an undergraduate at Nebraska, Edgerton earned an internship at General Electric's research laboratory in Schenectady, New York. After graduation from Nebraska in 1925, he continued to work at the GE lab before deciding to start graduate work at MIT in the fall of 1926.



THE MILK DROP CORONET, the famous photo of a drop of milk falling into a shallow dish.

Subjects that had intrigued him while working at the power company influenced his choice of research projects as an MIT graduate student. He sought to improve the efficiency of large industrial and utility synchronous motors. Both his master of science and doctor of science theses were on the mechanical and electrical shortcomings of those large motors and his recommendations for improving them. He received his master's degree in 1927 and his doctoral degree in 1931 from MIT, both in the field of electrical engineering.

While testing a motor in what was then called the Dynamo Lab at MIT, Edgerton noticed that the motor's armature appeared to be standing still when viewed in the flashing light from a firing thyratron tube. That observation was the start of his association with the stroboscope, a scientific instrument that could "stop" the actions of moving machines.

The armature of the motor was turning at hundreds of revolutions per minute, but in the flashing light from the thyratron it appeared to be stopped. He was able to see what was occurring in the motor under load conditions because of the *stroboscopic effect* made possible by human *persistence of vision*. Far more economical and efficient than taking motion pictures of the moving motor, the strobe effect made it possible for him to analyze motor faults as they occurred and correct them while standing there.

The human eye-brain response is too slow to react individually to two separate images that reach the eye within less than one-tenth of a second.

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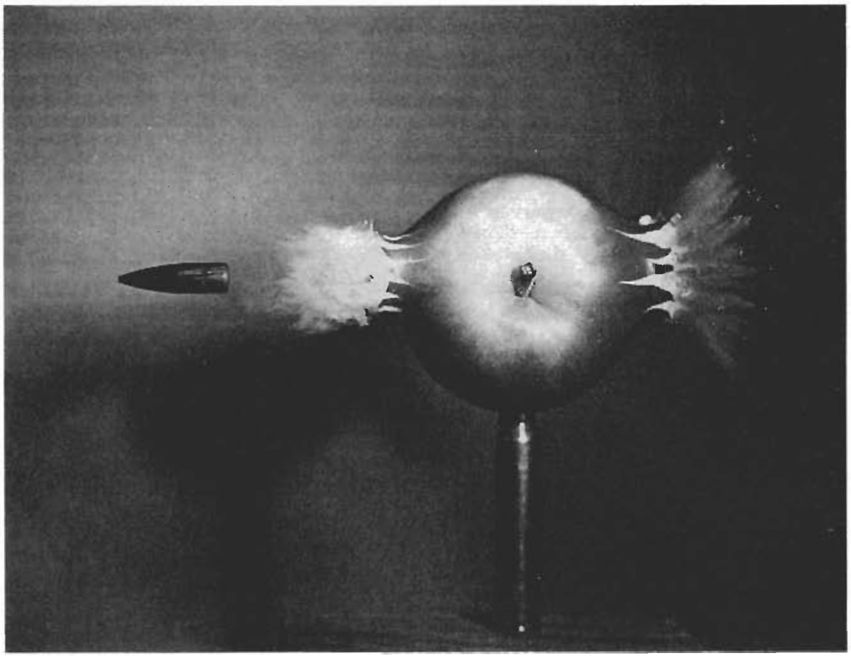
Thus, a succession of closely timed images following one another at brief intervals is interpreted by the brain as a seamless sequence. That is why the moving machine appears to be standing still.

Persistence of vision is the same response that makes it possible to view movies, television, and raster-scanned computer monitors. (See "Scanning Early TV," *Electronics Now*, July 1995, page 46.) Crude stroboscopes had been available as laboratory instruments as early as 1918, but they had not been used as industrial research tools.



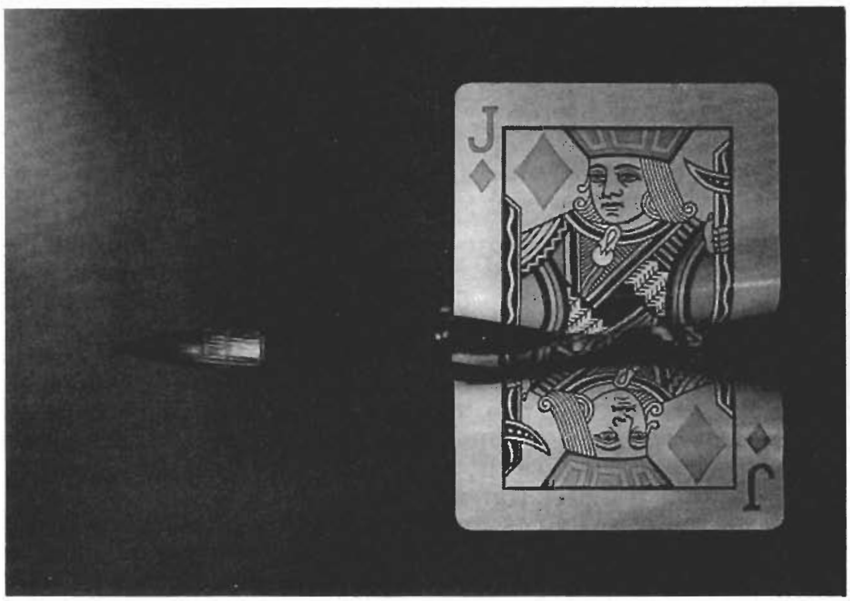
THIS .30 CALIBER BULLET, traveling at 2800 feet per second, was photographed with a one-third microsecond flash. The apple then flew apart.

Stroboscope history

Although the name Edgerton is virtually synonymous with the stroboscope, he did not invent the device. His association with the subject hinged on his ability to find practical applications for the instrument rather than for its invention. That honor goes to Dr. Peter Roget (1779-1869), who invented a mechanical form of stroboscope while studying the effects of persistence of vision.

In later developments, the Belgian scientist, Joseph Plateau (1801-1833), built a rotating device he called the *Phenakistoscope* in 1829 that created the illusion of continuous motion. His work was based on his own observations and Roget's earlier research. At about the same time, a Viennese scientist, Simon von Stampher (1792-1864), invented a similar mechanical device that he called a *stroboscope*, a name from the Greek meaning "to view a whirling disk." Both devices were essentially whirling slotted wheels bearing little resemblance to the modern electronic strobe.

After recognizing the value of the stroboscope for analyzing faults in moving machines, Edgerton built his own bench-type electronic model. Then, after modifying his invention to make it easier to manufacture, he arranged to have General Radio Corp., Cambridge, Mass. (now GenRad, Inc.), manufacture and sell them. These instruments later evolved into standard test instruments that were widely used.

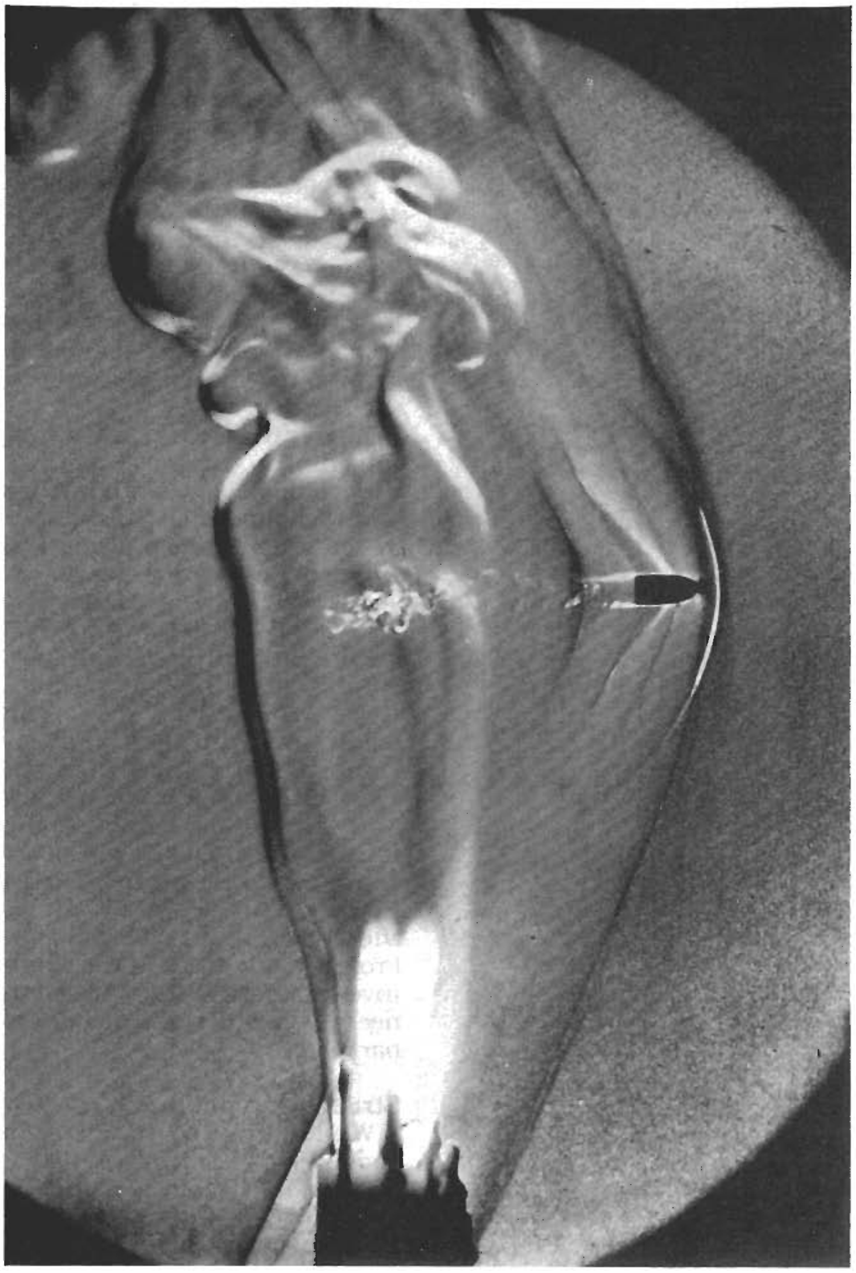


CUTTING THE CARD BY bullet.

Stop-action photography

In 1833, five years before the invention of photography, the English physicist Sir Charles Wheatstone (1802-1875), best known for his association with the bridge circuit of the same name and early forms of telegraph, suggested that short-duration light pulses from electric arcs would make fast-moving objects appear to stand still. He turned out to be right.

An early pioneer in photography, W.H. Fox Talbot (1800 to 1877), was the first person to demonstrate Wheatstone's theory. This Englishman had previously developed an independent photographic process that could print many positives from a single paper negative coated with silver iodide. Talbot made the world's first high-speed pho-



SUPERSONIC CANDLELIGHT. A photo showing a .22 caliber bullet passing through a candle flame.

tograph in 1851 when he put a copy of a newspaper on a whirling disk in a dark room and discharged a bank of Leyden jars (crude capacitors made as metal covered jars) to obtain a spark from an electrostatic discharge. The spark was bright enough to "freeze" the image of the whirling newspaper on the very slow photographic emulsions then available. The text from the newspaper captured in the photograph was readable.

The English scientist, Michael Faraday (1791-1867), also became interested in persistence of vision and stroboscopy. He is best known for his pioneering work in electromagnetic induction and as the discoverer of the basic principles of the electric motor. After observing that a moving toothed gear in a mill, when viewed through an adjacent moving toothed gear, appeared to be standing still, he built a small gear system in his laboratory (called Faraday's Wheel) to duplicate the phenomena. Although he made no real contribution to the subject, he provided Talbot with the battery and Leyden jars that were needed for his work.

High-speed photography was advanced by the invention of a gas-filled, light-emitting tube that could provide a controlled, continuous source of bright light. Its inventor, the German physicist, Heinrich Geissler (1814-1891), was seeking a continuous light source for spectroscopy. Later it was found that the Geissler tube could be pulsed.

An Austrian inventor, Ottomar Anschutz (1846-1907), devised the first practical high-speed mechanical camera shutter while attempting to animate high-speed photographs that he had sequentially photographed. His *Electrotachyscope* consisted of a large rotating disk and a Geissler tube, which he pulsed with a mechanical contactor. This apparatus made possible the generation of suitably bright, short-duration light pulses.

Other important early contributors to the wonders of strobe and stop-action photography included the English photographer, E. Muybridge (1830 to 1904), and the French physiologist Etienne Jules Marey (1830 to 1904).

Muybridge settled the ancient question about whether all four legs of a galloping horse ever leave the ground simultaneously. He set up a series of cameras a foot apart whose shutters were triggered by strings.

This setup provided a uniformly spaced series of photographs of a horse galloping along a track in front of the cameras. The pictures showed that there were brief periods when all four legs were off the ground.

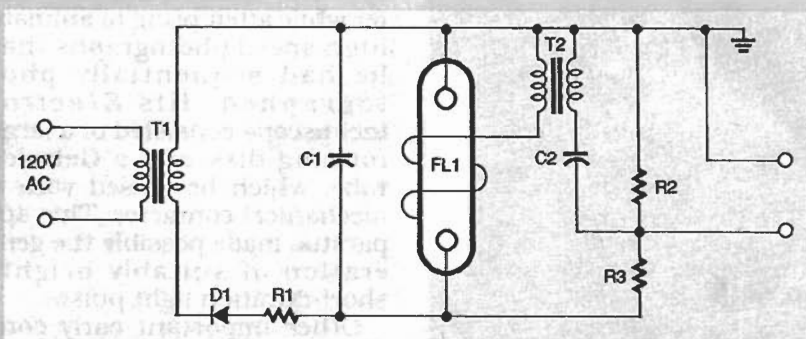
Marey introduced the principle of intermittent motion in 1882. He set up cameras that were able to make 12 exposures a second on a rotating glass plate with each exposure made at 1/720 second. His pictures of a jumper, for example, showed, on a single photographic plate, discrete changes of position as the athlete started and completed the jump. This work led,

FLASHTUBE TECHNIQUES

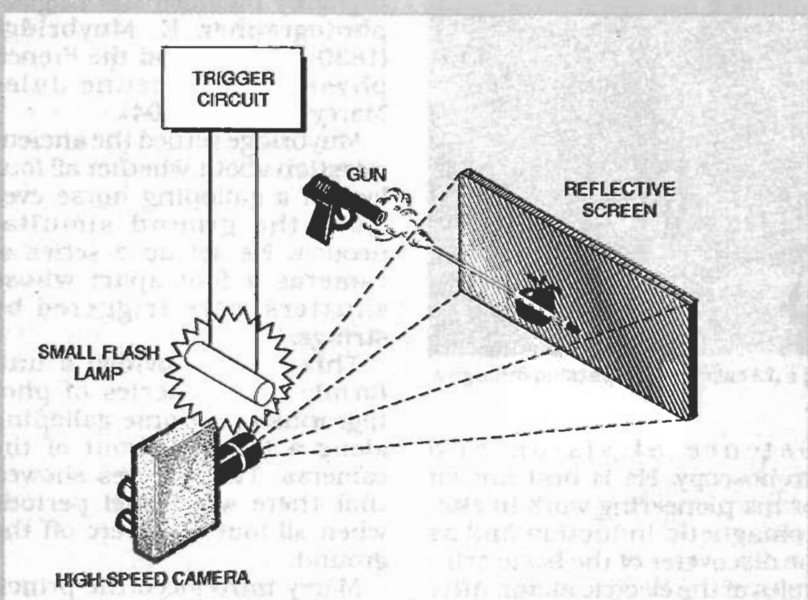
The figure shows an elementary circuit for triggering xenon-filled flash tubes with one external and two internal electrodes. The tube is connected across the main flash capacitor C1, which stores the energy that the lamp converts to light. Rectified current from transformer T1 charges capacitor C1 to a voltage equal to the peak voltage of transformer T1's secondary winding.

When switch S1 is closed, an electrical discharge begins in the flashtube. (S1 can be a contact in a synchronized camera shutter.) The pulse voltage in the secondary of the step-up transformer T2 is fed to the external electrode of the lamp to induce current in it by capacitive discharge. Once the glow on the tube walls begins, the lamp is lighted briefly but brilliantly by the capacitive discharge.

Multiflash, a term coined by Edgerton, is an electronic flash system (either single or multiple units) that can be fired manually or automatically in sequence. The interval between successive flashes and photographed images is determined by the activity being photographed. For example, when a golfer is photographed driving a ball, the flash might be fired automatically 100 or more times per second. A diver diving from a platform might be photographed only five or six times. Ω



METHOD FOR TAKING pictures of a high-frequency bullet in flight against a reflective screen.



TRIGGER CIRCUIT FOR FIRING an electronic flashtube.

more than 50 years later, to Edgerton's development of multiflash images.

Founding a consulting firm

In the years after Dr. Edgerton received his doctorate degree and became an instructor at MIT, the United States had entered a long period of economic depression. In the early 1930s, the salaries of instructors and professors were extremely low, and even the brightest college graduates had difficulty finding work in their chosen fields. Many of these people preferred to work at little or no pay rather than change fields to earn more money.

Two of Dr. Edgerton's graduate students, Kenneth Germeshausen and Herbert Grier, had completed their studies but were unable to get jobs. Edgerton was, however, able to persuade MIT to keep them on as unpaid research assistants in the Dynamo Lab.

This situation motivated Edgerton to think of ways that they could pool their knowledge and earn money as consultants to industry. He also wanted to supplement his own meager instructor's salary.

In 1931, Edgerton and Germeshausen formed a partnership to study high-speed photographic and stroboscopic techniques and their applications. Grier joined them in 1934. Edgerton, Germeshausen and Grier, Inc. was actually founded in 1947. (It later changed its name to EG&G.) However, during World War II, the Government's Manhattan Project made use of Edgerton's inventions while the three engineers were still working only as partners.

Strobes and photos

While pursuing his outside consulting activities and teaching at MIT, Dr. Edgerton was moving up the academic ladder. Something of Edgerton's personality emerges in this period of his life—his acceptance of the nickname "Doc" given to him by a colleague. It really emphasized his unique problem-solving abilities and his reputation as a mentor to graduate students rather than his possession of a doctor's degree. The MIT campus abounded with them at the time. "Doc" stuck for the rest of his life. He became a full professor of electrical engineering at MIT in 1948.

In the 1930s, Doc Edgerton's research was focused on stroboscopes for direct visual examination of moving machines. When stroboscopes were coupled to high-speed movie cameras, the stopped action could be recorded.

After investigating alternative light sources, he found that flashtubes were the only practical sources of the high-luminance, very short flashes of light suitable for ultra-high-speed photography. The light from magnesium flares could not be controlled, and the light from flashbulbs, although controllable with electronics, persisted too long.

The early experimenters in high-speed photography had used a spark gap, but it was satisfactory only where a small-volume source of very short duration is required. By contrast, the xenon-filled flashtube has an efficiency five times greater than the open spark.

The flashtube consists of a glass or quartz tube filled with gas and contains two or more electrodes. Other gases such as argon, neon, and krypton will work in flashtubes, but xenon provides the whitest light. These tubes can produce light pulses of one microsecond duration or less, and they can be fired thousands of times without needing replacement.

Because no satisfactory commercial flashtubes and trigger circuits were available commercially at the time, Edgerton invented his own. He developed a xenon-filled flashtube and trigger circuits that could produce the required high-intensity bursts of light.

Edgerton had a number of models built, and he sold them to professional photographers. This system later become a successful commercial product, and it remains the basic flash apparatus for still photography. The xenon flashtube also became an ideal stroboscope, and later xenon flashtubes would serve as optical pumps for pulsed lasers.

With his flash equipment Edgerton was able to make the photographs reproduced here. The bullets were traveling at speeds in excess of 2000 feet per second. The pictures, which possess artistic beauty, were of great interest and value to science and industry.

Aerial and undersea photos

In 1936, well before oceanography became a recognized scientific discipline, Dr. Edgerton developed his first underwater camera and lighting system suitable for use at extreme depths of a mile or more. He used a 16-inch naval shell as the container for both camera and strobe because it was strong enough to withstand the tremendous pressures at those depths. The naval shell was also large enough to house the bulky photographic equipment.

After the publication of his book *Flash: Seeing the Unseen by Ultra-High-Speed Photography*, the U.S. Army Air Force became interested in the use of strobe lamps for night aerial photography. After the United States entered World War II, strobe lamps became so important to the war effort that Edgerton was sent to England in 1944 to supervise the outfitting of aircraft with those lamps for night photography.

This equipment was used to photograph the Normandy beaches before the D-day invasion to confirm that there were no concentrations of German military equipment in the vicinity. Later Dr. Edgerton went to both France and Italy to advise the U.S. Army Air Force on night aerial photography. He was awarded the Medal of Freedom for his efforts.

Edgerton's services to the U.S. Government continued well into the post war period. During World War II, the government had used Edgerton's equipment to photograph atomic bomb explosions. After the war and the founding of Edgerton, Germeshausen and Grier, Inc., it was a natural transition for the company to support the Atomic Energy Commission (AEC) in its weapons research and development. The company was awarded contracts for managing atomic bomb testing. Edgerton-designed cameras photographed hydrogen bomb tests that were conducted both in Nevada and on Pacific Islands. These photos were vital in analyzing bomb performance.

After the war Edgerton also returned to underwater research and photography. He met with Jacques Yves Cousteau, the famed French undersea explorer and inventor of the aqualung, and began a decades-long collaboration in which Edgerton designed custom cameras for Cousteau, sometimes diving with him from Cousteau's research vessel *Calypso* to operate the equipment. The equipment was made by Edgerton, Germeshausen and Grier.

In 1953 Edgerton developed the "pinger," a high-frequency sonar projector that could determine precise locations on the ocean floor. In the process he discovered that the lower sonar frequencies partially penetrated the soft sediments on the ocean floor to reveal underlying rocks. Sonar beams from his low-frequency "boomer" located buried rocks off the coast of Puerto Rico that are believed to have been heaved up from the deepest layers of the Earth's crust.

Later, Edgerton designed the side-looking sonar that located the Union ironclad battleship *U.S.S. Monitor* (the cheesebox on a raft) which had sunk off the coast of North Carolina in a storm. This was the ironclad that had previously fought the Confederate ironclad *C.S.S. Merrimac* in the first battle between ironclads, March 9, 1862, off the Virginia coast. Edgerton was intrigued by the search for the Loch Ness monster in Scotland, so he had special sonar scanners and underwater cameras built in an attempt to track down the legendary sea serpent.

EG&G, Inc. now makes instruments and optoelectronic and mechanical components. Its products include devices that emit and detect light across the complete spectrum from ultraviolet to the far infrared. Although it still offers technical services to industry and government, it announced last year that it was ending its management and operating functions for the U.S. Department of Energy (DOE), successor to the AEC. Ω