INSIGHT

CAPTURING

The human desire to grasp the nature of fast phenomena has been driving technological progress for years, including in the field of ultrafast photography.

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Today, in this era of digital photography, people take dozens of photos every day, sometimes without even realizing it. When they notice something they like, they pull the phone out of their pocket and – snap! They can critique the shot immediately and re-take it if necessary. Most smartphones and digital cameras have many predefined settings that can cope quite well with poor lighting conditions, intense sunlight or even fast motion and still produce a quality picture. Photography has become so simple that even a complete layman, just using his or her phone, is able to capture images of a sort virtually unthinkable just a few decades ago.

The incredible technological advancement of recent decades now allows one to take photos with ultra-high sensitivity and quality. Even fast-moving objects or rapidly occurring phenomena no longer pose any great challenge. The sharpness of a photo is mainly defined by the time of exposure of the photosensitive component of the camera. This time is controlled by the speed at which the shutter opens and closes. Commercially available high-end cameras have shutter speeds of 1/8000 second, so the camera's sensitive component is exposed for only 0.125 milliseconds. As a result, capturing an amazing shot of a projectile whizzing by, a balloon bursting or a wine glass shattering is within reach of even inexperienced photographers.

From gallop to explosion

People have always been curious about processes whose details escape the human eye. The history of fast photography dates back

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THE INVISIBLE

Image of a water-filled balloon exploding, taken with a standard digital camera (DSLR) and a single laser pulse with the duration of 50 femtoseconds to illuminate the balloon.

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to the nineteenth century, the time of pioneering work by Eadweard Muybridge, a British photographer working mainly in San Francisco. In 1872, Muybridge was entrusted with the task of taking a series of photos of a galloping horse to answer the question whether there was any moment at which all the four hooves are off the ground simultaneously. The aim of this task was therefore to capture a photo of a phenomenon that cannot be seen with the unaided eye. Reputedly, this dispute was the subject of a $25,000 bet between two local businessmen with gambling in their blood. Their patience was put to a serious test as they had to wait for 6 years, until 1878, when technical capabilities finally allowed Muybridge to take a series of photos with a shutter speed of about 1 millisecond and prove beyond any doubt that a galloping horse does indeed lift its four limbs off the ground simultaneously for a moment. This project is considered to have been the cornerstone of ultrafast photography.

History tells us that technological development becomes especially intense during wartime, and the period of 1939–1945 was certainly no exception. The WWII years saw an important stage of development in ultrafast photography. In the early 1940s, Harold Eugene Edgerton, a specialist in electrical engineering, was employed by the United States government, together with his team, to photograph and film nuclear tests. The goal was to capture the explosion of an atomic charge less than a millisecond after detonation, in order to better understand the physical processes involved. For the project, the engineers designed what they called Rapatronic camera, to take a picture with a one nanosecond – that is, 10^{-9} second – exposure time. Instead of using a mechanical shutter as in Muybridge's camera, the Edgerton camera's operation was based on the polarizing properties of light. The engineer placed a Faraday cell between two polarizing filters arranged orthogonally (at a 90-degree angle) to each other. This arrangement of filters blocks the light falling on them. However, applying a short electrical pulse to the Faraday cell causes the light passing through the cell to change its polarization briefly, allowing it to pass through the second filter and reach the detector. The Rapatronic camera allowed Edgerton and his colleagues to take breathtaking photos of nuclear explosions during testing in the 1940s and 1950s.

Edgerton was a pioneer in using ultrashort flashes of light to capture quick events. He devoted almost his entire life to improving stroboscopic lamps and using their light for photographic purposes. This earned him the nickname "Papa Flash". Edgerton's work led to the broad use of stroboscopic lamps able to generate flashes of light with a duration of less than a microsecond. The flash of light in such lamps is generated by an electric discharge between two electrodes, occurring in the presence of high voltage (typically, a few kilovolts). Strobe lamps generating submicrosecond flashes are widely available and used in photography to this day. They generate light pulses short enough to take pictures of bullets on the fly without any noticeable blur. Over the years, Edgerton also used strobe lights to take pictures of balloons

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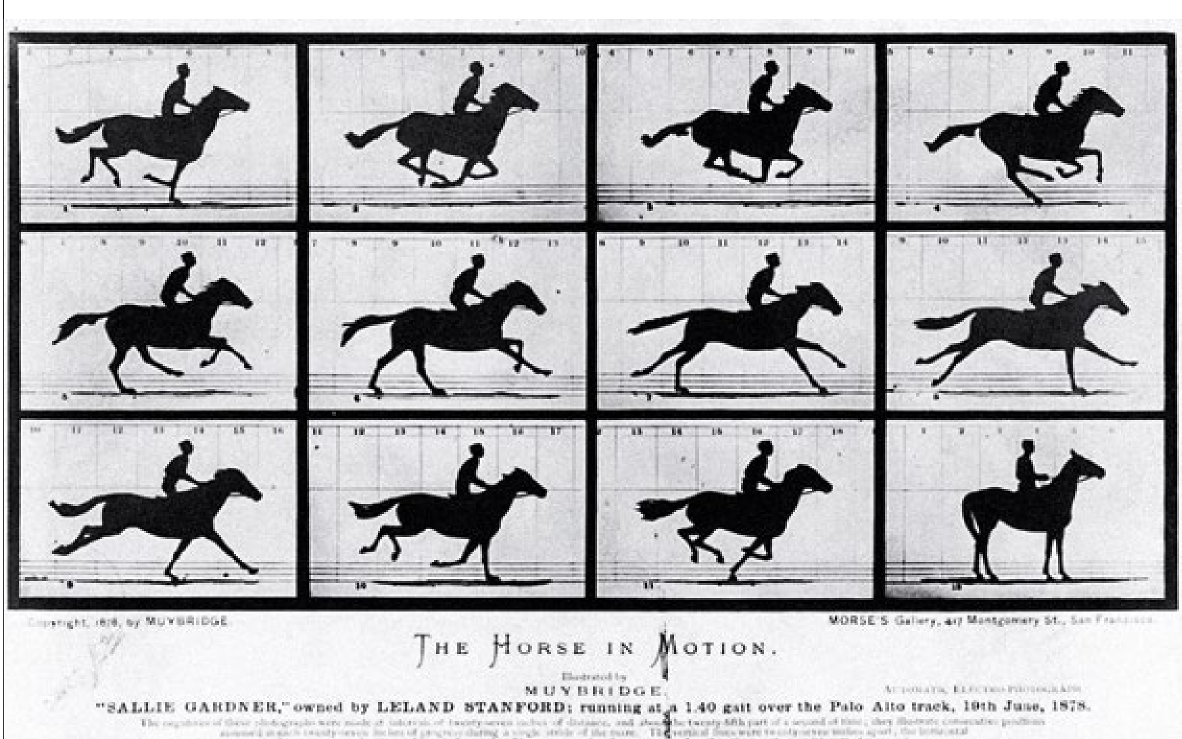
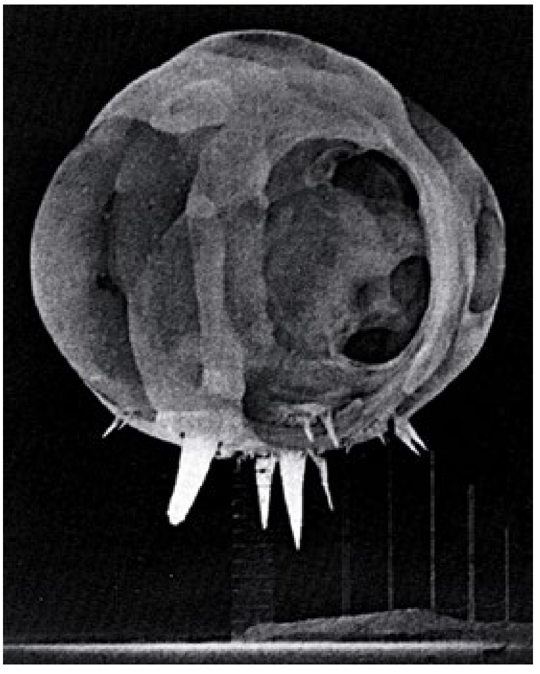


"The Horse in Motion" – a series of photos taken by Eadweard Muybridge in 1878, showing the subsequent movement stages in a horse's gallop.



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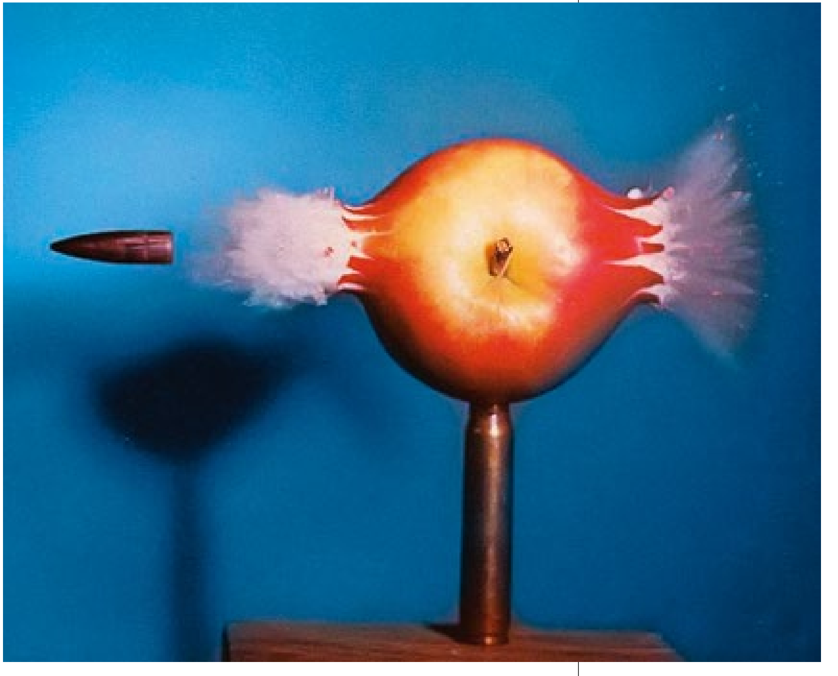

Left:
a nuclear explosion recorded about 1 millisecond after detonation. The photo was taken with the Rapatronic camera in 1952. The fireball's diameter is about 20 meters.

Right:
photograph showing the instant shortly after a bullet's passage through an apple (Harold Edgerton Archive, MIT, taken in 1964).

in various states of bursting, bullets hitting various targets, falling drops of milk, exploding glass vessels and many other fast events.

And here an interesting question arises: Is it possible to photograph phenomena faster than these – to take pictures with even shorter exposure times?

Water released

Over the past 10 years, my research work has been closely intertwined with the field of ultra-fast photography, the main idea of which is to capture what is invisible to the naked eye. The same concept is the basis of time-resolved spectroscopy and microscopy. My doctoral research involved studying how water molecules behave (how they move about, how they form and break hydrogen bonds) in systems of biological importance, how fast charges move in a single layer of graphene and at what rate high-energy charges relax in semiconductor quantum dots. These experiments are linked by one very important fact: their goal is to understand the nature of the fast processes taking place in these systems. Most such time-lapse experiments, whether carried out on the macro-, micro- or nanoscale, consist of two stages. In the first, the system's equilibrium is disrupted by an external stimulus. In the second, some kind of probe interacts with the system in order to "read" its current state. Because the dynamics of water molecules and charges usually occurs in femto- to nanosecond intervals, both the external stimulus and the probe usually take the form of short (pico- or femtosecond) laser pulses. The first one introduces the system into an excited state (oscillating, rotational or electronic), while the second (much weaker) monitors the state of the system. In a real experiment, the time after which the second pulse interacts with the sample is varied so that the probe reports the state of the system at different times from the excitation. This allows one to monitor the evolution of such a system, and thus to get accurate data on its dynamics.

Wishing to popularize ultrafast laser spectroscopy among the general public, while finishing my dissertation I completed a series of ultrafast photographs meant to reflect the quintessence of ultrafast spectroscopy and microscopy. At that time, I was working on the dynamics and interactions between water molecules, which is why I chose a water-filled balloon explosion as the subject of the pictures. I wanted to capture the moment just after the burst, when the damaged balloon is no longer surrounding the water contained in it, but the water still maintains the shape of the balloon. More importantly, in order to bond science with photography, I used individual laser impulses to make these pictures. Unlike standard discharge photography, where flashes of light last about one-thousanth of a second, in my photographs I applied the pulse lasting only 50 femtoseconds (less than a millionth of a millionth of a second). The way these pictures were taken was analogous to the ultrafast spectroscopic experiments I was conducting.

These ultrafast photographs reflect the ubiquitous interaction between light and matter in a beautiful way, and illustrate the interaction between water molecules and their dynamics in an artistic manner. Being more of aesthetic and artistic value than of scientific and cognitive value, these photographs

A photograph taken using a single pulse of laser light with the duration of 50 femtoseconds to illuminate the scene.

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decorated the cover of my doctoral dissertation; they were presented in several popular science articles in the Netherlands and Spain, as well as in a calendar published by the Catalan Physical Association (Spain) to commemorate the International Year of Light in 2015.

Illuminating the world around us

Various phenomena and processes imperceptible to the unaided eye occur both in the kingdom of plants and the kingdom of animals, and also in the everyday world of mankind. However, ironically, in the macroscopic world there are no events that actually require the use of such short, femtosecond flashes of light in photography! For example, hummingbirds flap their wings with a frequency of about 50 beats per second. The fungus *Pilobolus crystallinus* (also known as the Hat Thrower) is capable of firing off its spores at a speed of about 25 m/s. Thus, in order to capture these "fast" phenomena in a photo, it is enough to set the shutter speed at about 10 microseconds. One of the fastest available shotguns (the 0.220 Swift) fires rounds at a speed of about 1200 m/s. A shutter speed of 0.1 microsecond is enough to take a sharp photo of such a projectile in flight quite easily.

But not only small objects can move at enormous speeds. The International Space Station orbits around the Earth at a cruising speed of 7660 m/s. However, even for this space object, a similar shutter speed close to a microsecond is enough to take a sharp photo from 100 meters away. Light itself is considered the fastest thing in the universe. Interestingly, light, traveling at a speed close to 300 million m/s, moves "only" 0.3 meter in 1 nanosecond (in other words, 0.3 mm during 1 picosecond, or 0.3 micrometer during 1 femtosecond). Therefore, during the 50 femtoseconds when my flash of light illuminated the exploding balloon, the light itself only traveled 15 micrometers.

Ultrafast phenomena are extremely fascinating. People often do not realize their existence, even though their life depends on many chemical reactions occurring on tremendously short timescales. I am convinced that ongoing scientific and technological progress will bring numerous new discoveries in the sphere of ultrafast phenomena in the future, yielding ever more amazing and thrilling imagery.

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Further reading:

Piątkowski Ł., PhD thesis (2012), https://amolf.nl/publications/water-interacting-withinterfaces-ions-and-itself

For more on Harold Edgerton and his work, see http://edgertondigital-collections.org

For more on Eadweard Muybridge and his work, see http://www.eadweardmuybridge.co.uk

Gao L. et al. (2014), Singleshot compressed ultrafast photography at one hundred billion frames per second. *Nature*, 516 (7529): 74