# Explained: Femtoseconds and attoseconds

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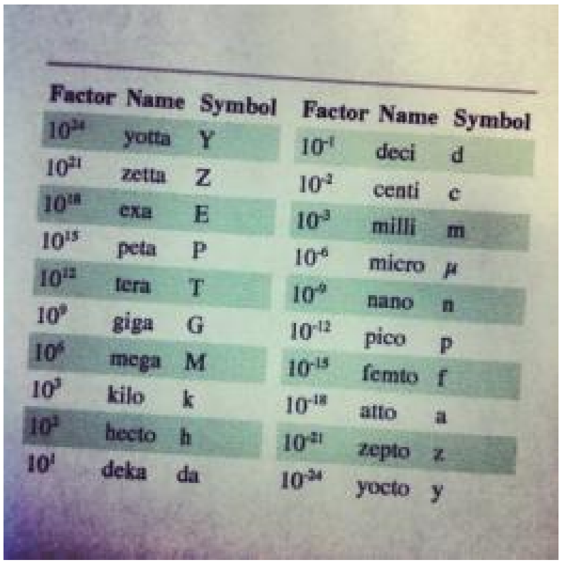

| Factor | Name | Symbol | Factor | Name | Symbol |
|---|---|---|---|---|---|
| $10^{24}$ | yotta | Y | $10^{-1}$ | deci | d |
| $10^{21}$ | zetta | Z | $10^{-2}$ | centi | c |
| $10^{18}$ | exa | E | $10^{-3}$ | milli | m |
| $10^{15}$ | peta | P | $10^{-6}$ | micro | μ |
| $10^{12}$ | tera | T | $10^{-9}$ | nano | n |
| $10^{9}$ | giga | G | $10^{-12}$ | pico | p |
| $10^{6}$ | mega | M | $10^{-15}$ | femto | f |
| $10^{3}$ | kilo | k | $10^{-18}$ | atto | a |
| $10^{2}$ | hecto | h | $10^{-21}$ | zepto | z |
| $10^{1}$ | deka | da | $10^{-24}$ | yocto | y |

Back in the first half of the 20th century, when MIT's famed Harold "Doc" Edgerton was perfecting his system for capturing fast-moving events on film, the ability to observe changes unfolding at a scale of microseconds—millionths of a second—was considered a remarkable achievement. This led to now-famous images such as one of a bullet piercing an apple, captured in midflight.

Nowadays, microsecond-resolution imagery is almost ho-hum. The cutting edge of research passed through nanoseconds (billionths of a second) and picoseconds (trillionths) in the 1970s and 1980s. Today, researchers can easily reach into the realm of femtoseconds

—quadrillionths (or millionths of a billionth) of a second, the timescale of motions within molecules.

Femtosecond laser research led to the development, in 2000, of a system that revolutionized the measurement of optical frequencies and enabled optical clocks. Continuing the progress, today's top-shelf technologies are beginning to make it possible to observe events that last less than 100 attoseconds, or quintillionths of a second.

Those prefixes—micro, nano, pico, femto and atto—are part of an internationally agreed-upon system called SI units (from the French Système International d'Unités, or International System of Units). The system was officially adopted in 1960, and has been updated periodically, most recently in 1991. It encompasses a total of 20 prefixes, 10 of them for decimal amounts, and 10 more for large multiples of the basic units (mega, giga, tera and so on).

The basic technological innovation that made it possible to observe changes at such tiny timescales was something called a pulsed laser, explains MIT adjunct professor of electrical engineering Franz Kaertner, who specializes in such devices. The technology was pioneered by Erich Ippen and Herman Haus in MIT's Research Laboratory of Electronics. "Erich and Chuck Shank, at that time working at Bell Laboratories, were the first to make femtosecond pulses, which were very difficult to create back then and are routine today," Kaertner says. Haus developed the underlying theory of how those systems actually worked.

The ability to observe events on such timescales is important for basic physics—to understand how atoms move within molecules—as well as for engineering semiconductor devices, and for understanding basic biological processes at the molecular level.

But physicists and engineers are interested in pushing these limits ever further. To understand the movements of electrons, and eventually those of subatomic particles, requires attaining the attosecond and ultimately zeptosecond (sextillionths of a second) range, Kaertner says. Achieving that requires pushing technology to produce pulses using higher-wavelength sources, and also producing pulses that encompass a wider range of frequencies—a more broadband source.

So far, Kaertner says, "the shortest pulse people have measured is 80 attoseconds." But various groups are working to push the limits even further, he says, using several different methods, including large-scale electron accelerators such as the Stanford Linear Accelerator.

High-energy X-ray pulses with femtosecond duration could make it possible to obtain detailed images, and ultimately movies, of the dynamics of complex protein molecules, Kaertner says—something that can't be done with existing techniques, and could be of great interest for biomedical research. But high-energy X-ray pulses that can probe these complex structures also destroy them in the process, so the pulse has to be so quick that the image can be obtained before the pieces fly apart.

"If the pulse is short enough, all the X-rays diffract from the protein before it is destroyed," Kaertner says. This is called diffraction before destruction. "It's a hot field at the moment," he adds.

Beyond basic research, femtosecond lasers have many practical applications as well. The most common are in the micromachining of materials and in Lasik eye surgery—which was enabled by the development of robust femtosecond pulsed lasers. These extremely short pulses made it possible to deposit high energy to destroy material such as tissue on a tiny spatial scale, without having enough time for the energy to diffuse and damage surrounding tissue, Kaertner says.

So, just how short is a femtosecond? One way to think of it, Kaertner says, is in terms of how far light can move in a given amount of time. Light travels about 300,000 kilometers (or 186,000 miles) in one second. That means it goes about 30 centimeters—about one foot—in one nanosecond. In one femtosecond, light travels just 300 nanometers—about the size of the biggest particle that can pass through a HEPA filter, and just slightly larger than the smallest bacteria.

Another way of thinking about the length of a femtosecond is this: One femtosecond is to one second as one second is to about 32 million years.

As a rough indicator of how relevant these terms are becoming, a recent Google search showed more than two million hits for the term femtosecond, but only about a tenth that many for attosecond, and a mere 16,000 or so for the next official term, zeptosecond—most of which were simply dictionary definitions, as opposed to actual uses of the term. (The final term in this procession, yoctosecond, produced a similar number.)

But as technology continues to march forward, there may be more talk about zeptoseconds and yoctoseconds—or, going in the other direction, things such as zettabytes of data or yottawatts of power—coming up in our future.

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