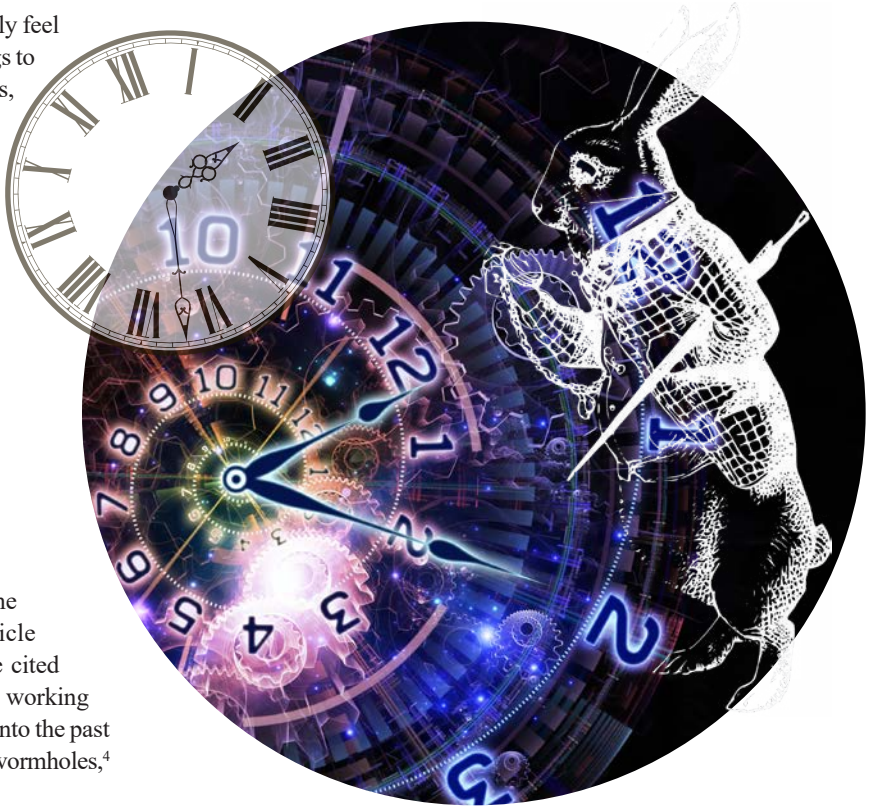
Tick-Tock

"I'm late, I'm late
for a very important date.
No time to say hello, good-bye,
I'm late, I'm late, I'm late."
- Lewis Carroll



With apologies to Lewis Carroll,[1] this is how I usually feel at the MRS Fall and Spring Meetings. So many things to do, so little time to do them. Tutorials, talks, posters, award ceremonies, exhibits, committee meetings. It boggles the mind! If only I could clone myself or figure out how to hop around in time so that I could attend multiple talks simultaneously. Alas, neither is an option.

While research is being conducted on cloning, nobody (to my knowledge) is working on the latter. That's because it's a hard problem. We have no idea what time is. One of my favorite science fiction authors, Clifford D. Simak, wrote a novel titled *Time Is the Simplest Thing*,[2] in which the protagonist was gifted by an alien intelligence with a mental ability that allowed him to physically travel through time. Alas, if only time were that simple. More than 100 years ago, Albert Einstein convinced us that our naive ideas about time are woefully inadequate.[3] [Note to self: This article is now bound to be cited many times because I've cited Einstein!] Researchers in general relativity are still working on these issues, with possible indications that travel into the past could be accomplished through exotic paths, such as wormholes,[4] but nobody really knows.

Tick-tock, tick-tock! *Carpe diem*. Time passes. All of us as humans are aware of time. We live in the moment, the fleeting instant of time that encompasses now.[5,6] We mark the passage of time in seconds, minutes, hours, days, weeks, years, decades, and centuries. Other than for developing instruments (e.g., clocks) to measure the passage of time, we mark the passage of time by events that affect us: birth, death, graduation, marriage, divorce, anniversaries, birthdays, love affairs, times of trouble, times of happiness, etc.

As materials researchers, we may mark time through other events: MRS Fall and Spring Meetings, submission deadlines for abstracts and manuscripts, publication of research papers, awards and honors we receive, conflicts with colleagues, committee meetings, reports, classes we teach, books we write, etc. However, if we are not careful, the time that we spend on our careers can overwhelm the remaining demands of life, creating conflicts with significant others and causing missed events involving children, family, and friends.

These become problems because our existence is relatively brief. We do not exist (at least in this plane of existence) on longer time scales, and our perception is extremely limited at shorter time scales. The fleeting instant of now leaves impressions on us that are augmented by further information that comes to us delayed in time through the distance that it has to travel as well as through information from other individuals. We have no direct sensory information about the future, although there are those who claim to be able to sense future events through clairvoyance. Our memories of past events are filtered by our ability to process information, the information (some true, some not) that comes to us after the fact, our own biases, our innate desire to feel good about ourselves, and other influences. Tick-tock, tick-tock.

And yet, as materials researchers, we are aware of events that occur on much longer and shorter time scales. At the cosmological time scale, the estimated age of the universe is nearly 14 billion years.[7] The half-life of a proton is estimated to be 10^{28}–10^{36} years.[8] The expected lifetime of the universe greatly exceeds either of those numbers.[9] At the shorter end of the time spectrum, the so-called Planck time is estimated to be ~5 × 10^{-44} seconds.[10] In between those extremes, we know that energy relaxation in excited atoms, molecules, and solids often

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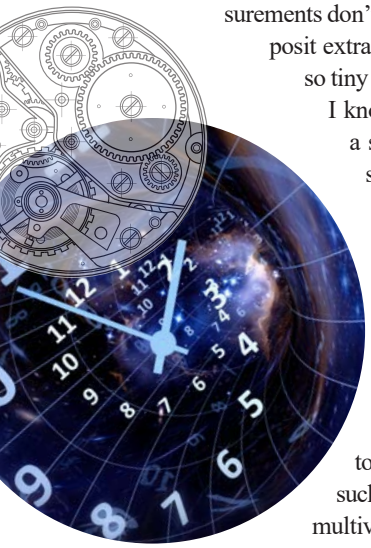
occurs on the picosecond (10^{-12} seconds) and femtosecond (10^{-15} seconds) time scales.

The shortest light pulses that have been produced in the laboratory are on the attosecond (10^{-18} seconds) time scale. Radioactive decay processes occur over both shorter and longer time scales.[11] Lifetimes of human-made products and structures range from a few years to millennia. The shorter time events are so short that we do not currently have any way to directly measure them. The cosmological time scales are based upon analyses that include the standard model of particle physics and our understanding of cosmology. If we lived really long lives, would that alter our perceptions and understanding of these long-time phenomena? If we could perceive time's passage on the attosecond or femtosecond time scale, would that alter our perceptions and understanding of short time-scale events? How much extra memory would humans have to have to live very long times and perceive events at the really short time scales. No wonder science fiction novels depict advanced alien races as having huge brains. Tick-tock, tick-tock.

Our senses seem designed to use information from three spatial dimensions and one temporal dimension. No one knows why. We can move repeatedly through the three spatial dimensions, but can only exist in the now.[5,6] The temporal dimension is experienced as an ordered sequence of points that moves surely in one direction, which we call the future. No random hopping about. No ability to alter the direction of time's flow. No ability to visit the future (other than through time's normal flow), and no ability to visit the past (other than through memory). Some attribute the direction of time's flow to thermodynamics and call it time's arrow.[12] But, does time's arrow emerge from thermodynamic behavior, or does thermodynamic behavior emerge from time's arrow? Tick-tock, tick-tock.



There are some models of gravitation (although recent measurements don't support this[13]) and string theory[14] that posit extra spatial dimensions that are said to be so tiny that we are unaware of them. As far as I know, however, these models only have a single temporal dimension. Although some have speculated about multiple time dimensions, I am unaware of any serious efforts to describe reality with a model that includes multiple temporal dimensions. [Note to self: I will now receive multiple missives from angry theorists claiming to have developed such models and explaining why their model is the only one to correctly account for reality.] Maybe such temporal dimensions exist through the multiverse[15] or something like it. $Tick_1$-$tock_1$, $tick_1$-$tock_1$. $Tick_2$-$tock_2$, $tick_2$-$tock_2$.. $Tick_n$-$tock_n$, $tick_n$-$tock_n$. Maybe there are multiple versions of me writing slightly different versions of this article, making slightly different mistakes, finding different references. Am I one of the average ones? Is mine the best? Maybe it's the worst. If you don't like this, don't blame me. The Steve to blame went down a different timeline or into a different temporal dimension. [Note to self: There are probably many who believe that I almost exclusively inhabit the imaginary plane.] $Tick_1$-$tock_2$, $tick_3$-$tock_4$.

Time is priceless to us. It is why we are who we are, and why we become who we will be. We learn and grow, but usually at an incredibly slow pace. That's because most of the interesting problems are incredibly difficult. Oh, sure, some people experience epiphanies that open them to understand phenomena both great and small! Some of that understanding even withstands the test of time and turns out to be correct. I've seen materials researchers experience epiphanies in the laboratory, in discussions with colleagues, and at meetings. I've even experienced a few. Time seems to slow down, and our senses seem to expand. We transition from a state of confusion to a state of certainty. Wouldn't it be great if we could bottle this, to pull it out and use it when we most need it? But sometimes epiphanies direct us away from the truth, down rabbit holes that only lead to Alice and the Mad Hatter.

I'd also like to be able to bottle my happiest moments and experience them again and again. Memory is such a poor substitute for the actual events. If I could re-experience events, many that I would choose would be from MRS meetings or with people whom I've met through MRS.[16–18]

Kurt Gödel, the eminent logician, published a paper in 1949 showing that time cannot exist in some universes described by the theory of relativity.[19] [Final note to self: Now that I've cited Gödel's work on relativity, the citations of this article should go viral.] Einstein, who was Gödel's friend and colleague in his later years at Princeton, wasn't very happy with this, but thought these universes would prove to be unphysical. However, Godel extrapolated his result to apply to our universe. Since I believe that our universe is described rather well by the theory of relativity, and I believe that we experience time, I'm interested in what this means. It seems almost as confusing as quantum entanglement, and "spooky action at a distance."

Steve Moss

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