Entropy and Currency

Time is what prevents everything from happening at once.
Space is what prevents everything from happening to me.
—Attributed to J.A. Wheeler, http://en.wikiquote.org/wiki/Time

Money, like the calendar and the system of measurements, is a cultural construct that may have arbitrary aspects, but to function properly it needs stability and predictability.
—J. Weatherford, The History of Money, *Three Rivers Press, 1997, p. 267.*

Dynamics can't happen without time. "*xdot*" propels solutions forward, predicting the future. The problem with time is that many equations can be run backward as well as forward, so what guarantees that time can go only forward? The math trick of replacing t by $-t$ doesn't convince me that the monotonicity of time is a problem worthy of serious attention. By analogy, I could set the value of a mass to be negative, but I don't feel compelled to ponder the meaning of anti-inertia. Nevertheless, many researchers have investigated why time marches inexorably forward.

The popular physics literature is quite taken with the question of the "arrow of time." The way I understand it, time can—at least in theory—go backward but doing so is highly improbable. A large number of particles makes it highly unlikely that heat will flow from cold to hot, a sure sign that time is running backward. So, for physicists, that settles that.

On the other hand, explanations from physics aren't always completely convincing from a systems-and-control point of view. "Which system-theoretic concept nails down the arrow of time?" I wondered. Since lots of particles are needed to make time monotonic, I guessed that high dimensionality is the culprit. So, why not write down the familiar *xdot equals Ax* with a high-dimensional vector x and *prove* the arrow of time, at least in the linear case? After all, a proof is the gold standard for publishing in prestigious controls journals; physics alone just doesn't cut it. Unfortunately, the arrow just didn't seem to be hiding in such a plebian setting. Something was missing, but what?

TRICIA YURKOVICH

Steve Yurkovich, former *IEEE Control Systems Magazine* editor-in-chief, and Dennis Bernstein pose at the top of the Giralda bell tower of the Santa Iglesia Catedral in Seville, Spain.

Since I couldn't realistically expect to model every particle in the universe, it occurred to me that uncertainty might be the arrow driver. But uncertainty exists in the mind of the modeler, as we like to say in robust control. It just doesn't seem reasonable to think that time goes forward simply because I personally don't know what every particle is doing. Unfortunately, it wasn't obvious how to reconcile uncertainty modeling with probability arguments from physics.

But it also occurred to me that those little particles do a lot of colliding in three dimensions, and that kind of interaction is pretty nonlinear. So, while dimensionality and uncertainty aren't the keys to the arrow, maybe nonlinearity is what makes time tick. To make things as simple as possible, why not look for a proof in the low-dimensional, nonlinear case? That setting raises the possibility of sensitivity to initial conditions—a key agent in chaos. Perhaps chaos is at the heart of the arrow. Better yet, since billiard balls are chaotic, wouldn't zillions of colliding balls do the trick? Maybe what I needed was a system that was both nonlinear *and* high dimensional.

In the midst of this speculation, I observed that the clock on my wall keeps

About This Issue

Having pondered the meaning of time in this issue, I think it's only fitting to consider the meaning of energy. Energy has the units of force times distance, and thus force, which makes particles move, is a kind of vehicle for transmitting energy. Moving particles have kinetic energy, and they gain potential energy when they're raised to a higher state. Although these kinds of energy are manifested differently, energy is the unifying quantity.

Energy shifts effortlessly from kinetic to potential to chemical and then back to kinetic, much like money passing from cash or bonds to goods and then back to cash, changing form but retaining (hopefully) its value. We often say that energy is conserved, but we acknowledge that mass can be converted to energy, and I like to think of mass as a kind of precipitated energy.

To complete the circle—and mystery—we should note that energy depends on both mass and time, actually, time squared, not to mention length squared. So I'm inclined to think of energy as a kind of distillation of mass, time, and space.

While working with Mike Walker and Alfredo Pironti on this second part of the special section on tokamak plasmas, a thought occurred to me as I filled up the gas tank of my car. In particular, I realized that it wasn't the gas that I wanted but rather the energy *in* the gas. The petrol was simply a medium that carried the energy, and an annoying medium at that, occupying mass and volume and contributing pollution as I drove around.

So how could I get energy without liquid fuel? One alternative is batteries, which can be recharged over and over. However, one of the points raised by Ken Schultz in his article "Why Fusion?" is that energy is difficult to store. Unlike money, which I can deposit in a bank, it's remarkably difficult to save up energy for the future. Besides batteries, how can energy be stored? One approach is the Sisyphean facility on the top of Northfield Mountain in my home state of Massachusetts. This facility pumps a huge quantity of water to a lake on the top of the mountain, only to have the water flow back down later so that the energy can be "recovered" (at a remarkable 75% efficiency).

Surely, I thought, there are much better methods for storing large quantities of energy. During the Conference on Decision and Control (CDC) in Seville, Mike disabused me of this notion. Short of stacking up millions of batteries, water pumping is about the best we can do right now. So Ken's point is this: wind and solar are wonderful technologies—and we all hope for their success—but any energy-capturing/-producing technology that is intermittent requires excess-energy storage for times when the energy source is unavailable. With fossil fuels beginning to dwindle and causing increasing havoc with the climate, and with nuclear fission resulting in caustic waste that will be problematic for generations, we have little choice but to look toward fusion, which just happens to be *the* killer app of control technology.

This issue of *IEEE Control Systems Magazine* presents four feature articles to complete the special section on tokamak plasmas. In addition to Schultz's article "Why Fusion?" we have a comprehensive article by Walker, Humphreys, Mazon, Moreau, Okabayashi, Osborne, and Schuster on control-related challenges in tokamak development. The next two articles focus on specific tokamak devices. The JET tokamak in Culham, United Kingdom, has provided a wealth of knowledge and experience in controlled plasmas. This article is coauthored by Sartori, De Tommasi, and Piccolo. The final article, by Lister, Portone, and Gribov, provides a detailed discussion of the plans and challenges for the ITER tokamak, now planned for construction in France. The challenges are daunting, but success in this endeavor is essential.

One thing I have observed in my years in research is that progress comes from unexpected directions. A crucial insight in one narrow field, unnoticed at first, is amplified and generalized, slowly but surely, until it makes a significant impact on diverse fields. I think about this model of technology diffusion as I read about the challenges of fusion. The researchers working to develop this technology are the front line in solving a gargantuan problem. The rest of the research world, working on problems that have little apparent relationship to the direct challenges of controlled fusion, provide a kind of supporting pool of innovation. Crucial ideas and technology could bubble up from any direction. The technology roadmap is long and winding, and none of us can predict where critical advances might come from. If controlled fusion succeeds, then I'd like to thank that all of us contributed a little bit to its success. In fact, its success may depend on all of our efforts, either directly or indirectly.

—DSB

time by moving steadily and predictably forward. The clock just seems incapable of running backward, I thought. Pulling a barbed hook out of the mouth of a fish, driving a worm gear backward, or reversing the direction of an ancient clock escapement all seem to suggest that some nonlinearities are stamped "forward only." Perhaps high dimensionality is a red herring, and unidirectional nonlinearities are the key.

Or maybe not. I thought of a shattered pane of glass, easy to break but hard to put back together. It would be quite a feat to find the right combination

LUCY PAO

Frank Doyle, editor-in-chief of *IEEE Transactions on Control Systems Technology*, Christos Cassandras, editor-in-chief of *IEEE Transactions on Automatic Control*, Tariq Samad, IEEE Control Systems Society VP of Publication Activities, and Dennis Bernstein meet during the IEEE CDC to discuss IEEE publication plans.

of force and heat to reconstruct the original window from the fragments. I envisioned an unimaginably miniscule domain of attraction that, once exited from, is almost impossible to reenter. So, maybe tiny domains of attraction prevent time reversal.

After searching and searching for a proof of the arrow of time, it occurred to me that all of my conjectures were hopeless for a very simple reason: All of the underlying equations are based on time, and I don't know what time *is*. A monotonicity proof would amount to nothing but vacuous arguments.

I eventually gave up trying to prove the arrow of time in a system-theoretic way. But the problem occurred to me again when I stumbled upon a fascinating book on the history of money. I learned about the many forms of money, its evolution, its manifestations, and its critical role in the rise and fall of civilizations. But the one question I was curious about—what is money?—never seemed to be answered. In fact, I began to suspect that economists themselves might not really know what money is.

Since most people are paid by the hour, and since money can be used to speed some things up, I realized that time and money are somewhat interchangeable. These puzzling quantities seemed to have a kind of cosmic interconnection that was far from coincidental. But despite the clock on my wall and the paper in my wallet, I felt helpless in penetrating this mystery.

I've since decided that it would be wise to stop worrying about what time and money are. Nevertheless, whenever I drive by a bank, where money is stored, lent, and transformed, I wonder whether those inside ever stop to ponder what it is they're manipulating. For me, I'll stick with something I'm sure of: *xdot equals Ax*.

Dennis S. Bernstein
Editor-in-Chief
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Fortuitous Failure

United 232 was also blessed with a great deal of luck. The crisis occurred during daylight, in good weather, and in reasonable proximity to an airport. "Had any one of these factors been different, the outcome would have been different. … The captain said the number one factor was luck. After the accident, they reprogrammed the scenario into a flight simulator, and on 35 attempts, they couldn't get anywhere near the runway." In fact, based on these simulator exercises, the Safety Board concluded that "landing at a predetermined point and airspeed on a runway was a highly random event….[Such] a maneuver involved many unknown variables and was not trainable, and the degree of controllability during the approach and landing rendered a simulator training exercise virtually impossible."

— T. Homer-Dixon, The Ingenuity Gap *(Vintage Books, 2002, p. 19).*
An engine failure on United Flight 232 damaged the hydraulic system that controlled the rudder, elevator, and ailerons. Of the 296 persons on board, 185 survived.