



Tracking Technological EVOLUTION

By Krista Zala

TECHNOLOGY: IT'S EVERYWHERE. Even on getaway walks in the woods, we wrap ourselves in revolutionary materials and pack along a breakthrough or two in communications. Technology is so deeply embedded in our culture that, like the air we breathe, we often take its presence for granted and notice only its lack.

Today, in fact, we're living in a Cambrian explosion of technological diversity. Amid the



SFI External Professor W. Brian Arthur has found that new technologies derive their being from existing ones, evolving similarly to a coral reef that builds itself out of itself.

“One of the biggest questions is how the world is changing through technology,” says Béla Nagy, a statistician and former postdoctoral fellow at SFI. Working with SFI Professor J. Doyne Farmer and former SFI Omidyar Fellow Jessika Trancik, Nagy measures progress across its many forms. “By collecting data about how technology evolves, we’re investigating whether we can predict its future,” he says.

If measuring how fast technology changes sounds like a formidable task, consider the most accessible indicator: cost. The cost of a good reflects how well we apply technology to optimize its production—and it provides a means to compare apples and oranges or VWs to Fords or flat-screen TVs to roller coasters. Historical trends tend to show that cost drops with increased production, in what’s known as a performance curve. Sampling performance curves of various products and abilities, then, offers a means to find trends in improvement.

To do so, Nagy and colleagues created a repository for researchers to donate their data sets. Most donors had collected their data for their own specialized studies, which makes for an eclectic mix of metrics, Nagy says. The website (pcdb.santafe.edu) features performance curves of wheat and wind power, Model-Ts and monochrome TVs, energy storage and information storage.

Despite the variety, the researchers are finding patterns. “The sources are heterogeneous and the technologies are completely different, but they all seem to support empirical laws,” says Nagy. (Laws in this context are understood as malleable guidelines, not like the more rigid laws of thermodynamics and gravity.) Nagy and colleagues found that Moore’s Law, which predicts that every two years we can double the amount of memory stored in a given size chip, applies in a general way to technological progress: while each product has its own rate, performance curves follow an exponential improvement over time.

merry chaos of touchscreens, jet engines, and MRIs, researchers at the Santa Fe Institute are looking for themes connecting these seemingly unrelated advances. By studying technology’s patterns of development, they are finding laws that govern its progress, modeling how best to direct them, and even sketching a theory of how technologies arise and develop and take their places in society.

“The surprising thing is that we see universalities,” agrees Farmer. “It’s even more surprising for other colleagues, because they don’t believe such laws exist in the first place.”

They hope to expand the database into an Archive of Technology. By ramping up acquisition, catching fleeting data, and running it for decades, Farmer suggests they could apply it to other ambitious ventures such as solving policy questions about government investment strategies.

For now, the performances they’re tracking can potentially keep improving for a while.

“In most cases, technologies are a long way from fundamental physical limits,” says Farmer. For example, we might approach transistors’ physical limits within a decade as we shrink them to a single atom. But by then, if large-scale quantum computing becomes possible, it could change the game completely, as transistors changed vacuum tube systems and as vacuum tubes changed mechanical switch systems. In that case, explains Farmer, the variation on Moore’s Law they are proposing would evolve too, mutating from specifically governing transistors to a more general law of computation power.

Breakthroughs like quantum computing con-

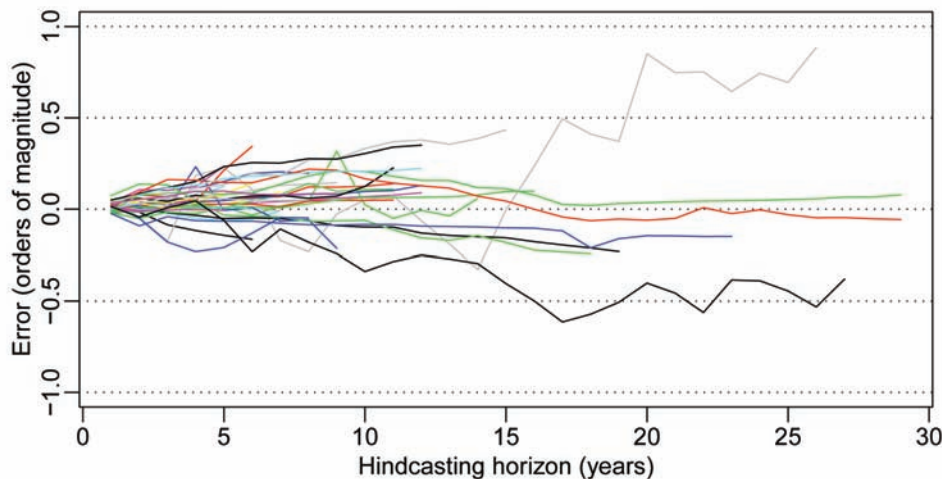
found the patterns of technological evolution. Both vacuum tubes and transistors, for instance, revolutionized computing power and re-launched it on a higher, faster trajectory. But even though the precise type and time of a breakthrough cannot be pinpointed, Nagy suggests that we may one day be able to predict their likelihood, as seismologists do earthquakes.

If quantum computers are built, they are still years and millions of dollars away. And they are just one of thousands of promising projects competing for research and development funding. Limited budgets raise the question of how to fund technological innovation to move societies toward the healthiest possible future. Perhaps the most urgent example lies in the energy sector. With the need to change our energy structure within 50 years to reduce carbon levels, the pressure is on to do so at the lowest possible cost to society.

Unfortunately, “anything that’s cleaner is also more expensive,” explains James McNerney, a PhD student in statistical physics at Boston University and a graduate fellow at SFI. “That’s why people in the energy and climate change world rely on performance curves.” For example, solar power is much pricier than carbon-intensive energies, but

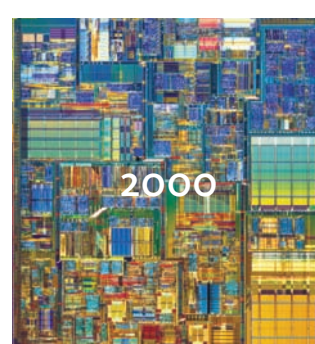
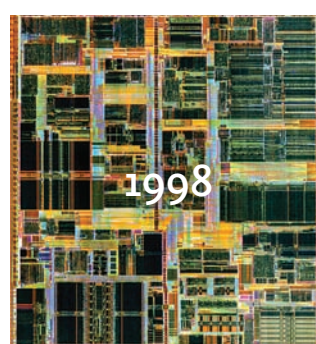
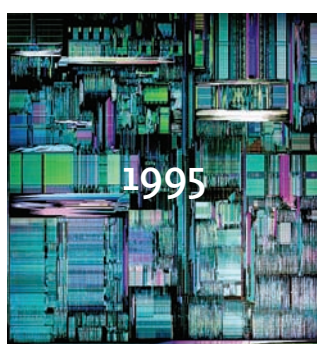
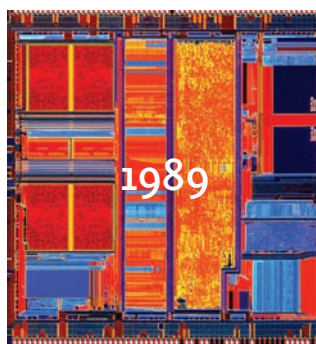
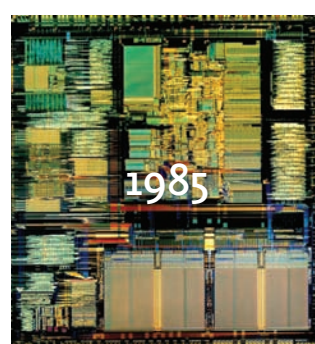
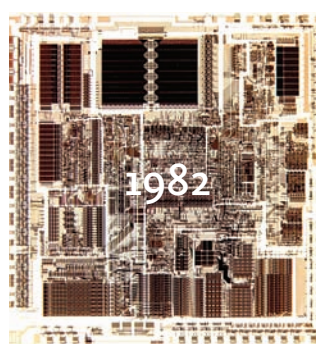
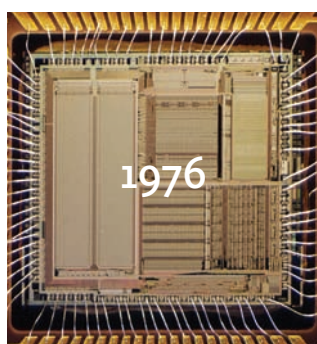
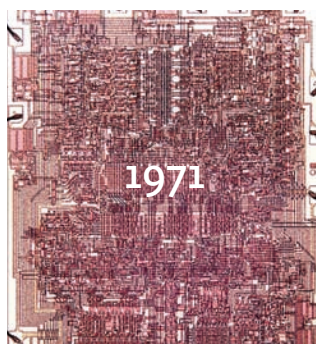
most of its components are getting cheaper. In contrast, nearly half the cost of coal-powered electricity remains fixed (the cost of coal hasn’t changed much in a century, and it hasn’t made economic sense for power plants to squeeze more energy from it since the 1960s) so its curve changes little. When, if ever, will coal meet solar in cost? How much should we invest now in solar power to hasten that event?

Solar power’s multiple sophisticated technologies uncover another quandary: the more elements a product has, the more opportunities for improved efficiency and lower price points. But, in the same way that a big organization is often slower to change than a



Like Moore’s Law, Wright’s Law offers a functional form for expressing the relationship between experience and production. This graph tracks 37 technologies, each with a history of at least 15 years. The price history in the first 10 years is used to forecast prices in the following years. These are forecasts with the benefit of hindsight, hence referred to as hindcasting. The horizontal axis represents this hindcasting, which is the difference between the 10th year and the target year of the hindcast. The vertical axis shows the difference between the predicted and the actual price on a logarithmic scale (base 10).

CHART: COURTESY OF BELA NAGY/SANTA FE INSTITUTE



INTEL.COM IMAGE LIBRARY/TAYLOREDGE.COM

small one, the complexity of a technology can slow its rate of evolution. To find out what slows the rate, McNerney and colleagues recently modeled the interactions between components of a system, looking at how changing any given part affects the rest. They discovered that the number of components may matter far less than their connectivity: the more interconnected the parts, the slower the evolution of the whole.

Though it may be tempting to concentrate efforts on less-interconnected technologies with more potential for quick evolution, there's danger in focusing too narrowly.

"No single technology is going to solve our energy problems," points out Trancik, an assistant professor at MIT's Engineering Systems Division. Trancik studies the driving forces of innovation and their influences on the global energy mix, particularly amid new demands arising from climate change concerns. To address climate change, we have a few policy options, she explains: we can invest in research and development, raise the price of carbon through a tax or cap, or create guaranteed markets where energy companies must draw a given percentage of their power from certain low-carbon technologies.

Drawing from the performance of energy

The increasing complexity of these Intel computer chips illustrates a general principle of technological progress: while each product advances at its own rate, performance curves follow an exponential improvement over time.

options today and how each has changed, Trancik models how best to invest in their technological development. Whether it's a carbon tax or a breakthrough in photovoltaics, a change in one energy source ripples through the market, affecting the competitiveness of other options. From capital costs and conversion efficiency, to demand- and supply-side dynamics, there's no shortage of factors to consider. Such complexity means no single answer emerges, but seeing how the myriad drivers affect innovation and carbon emissions is essential for making informed decisions.

The generalization of Moore's Law that Trancik, Farmer, Nagy, and McNerney are finding in performance curves raises the question of whether technology conforms to a set of principles in its overall evolution. Not surprisingly, another SFI thinker has explored just that.

Economist, engineer, and mathematician W. Brian Arthur (SFI External Professor and visiting researcher in the Intelligent Systems Lab at the Palo Alto Research Center) has worked for much

Novel technologies come into being by combining ones we already have: the laser printer is put together by combining the operations of a laser, computer, and Xerox machine.



Understanding technological advancement has become urgent, especially in the energy sector. SFI researchers are exploring competing energy sources to help society move cost-effectively toward a healthy future.

of his career on the economics of technology. His curiosity about how economies arise led him to realize he needed to ask where technologies come from. A dozen years later, he has laid out the principles and mechanisms to an evolutionary theory of technology in his 2009 book, *The Nature of Technology: What It Is and How It Evolves*.

In it, he explains that all technologies are put together—are constructed—from existing technologies. Novel technologies come into being by combining ones we already have: the laser printer is put together by combining the operations of a laser, computer, and Xerox machine. This doesn't mean of course that the MRIs and jet engines of today are combinations of the pottery and arrows of 10,000 years ago. From time to time new phenomena are captured and harnessed into use. X-rays, for example, were discovered in 1895 and

consequently enabled the innovation of X-ray radiology. Similarly, the principles of quantum mechanics, discovered more than a century ago, are just now being summoned for quantum computing.

All novel phenomena are taken from somewhere in nature. Even behavioral changes, like the collective social agreement that a piece of paper has monetary value, arguably have natural roots. This ongoing agglomeration of old elements with the occasional addition of new phenomena to constantly form new technologies is what Arthur describes as combinatorial evolution: new technologies derive their being from existing ones, or, as he puts it, technology—the collection of all technologies—evolves by building itself out of itself. Arthur compares this process to a coral reef building itself out of itself. And as with a reef, innovation is a far more social process than the stories

of lone inventors would have us believe.

Clearly, designers can combine technologies more freely than animals can speciate. But once a new technology exists, its variants encounter plenty of Darwinian selection that determines whether it finds a niche in the economy or is consigned to the curio cabinet of civilization.

Where, then, might we be headed with our turbo engines and DNA microarrays, our gene splicing and space stations? Arthur hopes we apply them to improve the human condition by relieving suffering and extending qualities of life. Ultimately, despite all the delights and horrors it can evoke, technology itself is neutral. It's up to us how we use it. ◀

Krista Zala is a science writer living in Victoria, B.C. She can be reached at kristazala@gmail.com.