AHEAD OF THE CURVE

DOUGLAS ALLCHIN, DEPARTMENT EDITOR

Graphs function plainly to summarize data. They hardly seem momentous. Unlike a famous discovery, whose significance is often marked by an eponymous name: *Mendel's* laws, the *Watson & Crick* model of DNA, *Darwinian* theory. Who would name a mere graph? They seem mundane fragments of science, hardly worth celebrating. A notable exception, however, is the Keeling Curve (Figure 1). This "simple" graph depicts the steady rise in the concentration of carbon dioxide (CO_2) in the Earth's atmosphere over the last half-century. It helps document how humans have transformed the atmosphere and, with it, the Earth's temperature. The Keeling Curve is a linchpin in the evidence that humans have changed the planet's climate.

The Keeling Curve starts in 1958 and continues uninterrupted for over five decades. The scale of the data is extraordinary, an ideal rarely realized in science. The "hard" data from real-time measurements show the steady accumulation of CO_2 from burning fossil fuels. It serves to warn an energy-hungry culture of its environmental hubris. Although "just" a graph, it is monumental in scope and significance.

The Keeling Curve, viewed in retrospect, raises an interesting question about how science works. How do such important long-term data sets emerge? Often we assume that scientific investigations find just what they intend to find. That is an implicit lesson of the tidy "Scientific Method," typically inscribed in textbooks. But can we trust this Sacred Bovine? Could anyone have predicted this curve or its importance in advance? How did these important data *originate*? What happened *before* the graph was fully created? What happened, literally, ahead of the Curve?

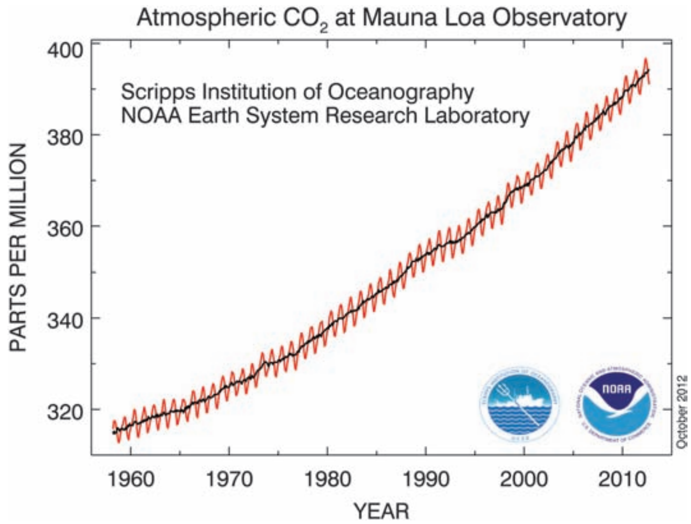

Figure 1. Source: http://www.esrl.noaa.gov/gmd/webdata/ccgg/trends/CO2_data_mlo.png.

○ A Measured Approach?

The Keeling Curve is named after its creator, Charles David Keeling. In the 1950s, as a handsome young man frequently enjoying the great outdoors (Figure 2), he hardly fit the stereotypical image of the scientist clad in a white coat, isolated in a lab. Indeed, with a fresh degree in chemistry, he turned down many job opportunities because he wanted to be closer to nature on the West Coast. As an initial project in his new position, he focused on how to extract uranium from granites, for use in nuclear power. After two weeks of crushing rocks, however, Keeling felt uninspired.

Then he overheard a small geochemical puzzle. Could one determine the carbonate level of surface water by assuming it was in equilibrium with the carbon dioxide in the air above and the carbonate rocks below? Soon, Keeling was driving up the dramatic Big Sur Coast of California, camping amid the redwoods, and waking every few hours at night to collect air, river, and subsurface water samples. Back home, he rigged up an apparatus to measure the scant amounts of carbon dioxide in his air samples (less than 1%). He needed some technical expertise to secure precise and reliable measurements. Keeling's results indicated that the original idea was ill founded. The carbon dioxide dissolved in water was much more concentrated than in the air. But he also noticed that the CO_2 concentration of the air was relatively constant, rising at night. Keeling now had a reason to measure atmospheric CO_2.

At the time, such measurements of CO_2 ranged widely. Scientists thus assumed that it varied from place to place, due to unknown local factors. Now intrigued, Keeling wondered if there was a consistent baseline and an identifiable pattern to the variation. Over the next year he collected samples from more than a dozen sites across the West Coast – while appreciating the forest, desert, mountain, and seashore scenery along the way. Keeling found that CO_2 levels reflected the density of local vegetation, but otherwise seemed surprisingly constant, especially where winds mixed the air well. He was now convinced that there was a standard level of atmospheric CO_2 globally.

An opportunity to expand his studies emerged the following year. As the Cold War took hold, the U.S. wanted to know more about the Earth – for example, for detecting enemy submarines in the oceans and for gauging the possible effects of nuclear weapons. It was all framed in the guise of international cooperation: the International Geophysical Year, 1957–1958. The military was also concerned about the ability of

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Figure 2. David Keeling in 1958, around the time he started collecting global data on atmospheric CO_2. (Courtesy of the Keeling family and the Scripps Oceanographic Institute.)

carbon dioxide in the air to absorb heat and whether that might affect heat-seeking missiles. So the Weather Bureau was already set to measure CO_2. Keeling's proposals were well received, and he was able to establish remote CO_2 measuring stations in Antarctica and at windswept Mauna Loa, in the middle of the Pacific Ocean, as well as at the Scripps Institution in California. Roughly two years later, Keeling still had no consistent CO_2 measurement. Instead, however, he had documented a seasonal flux in CO_2, due to the deciduous forests in the Northern Hemisphere.

Keeling wanted to continue. He secured money from the still young National Science Foundation (NSF), recently more richly endowed in the wake of the Soviet launching of the satellite Sputnik and consequent U.S. anxieties about losing superiority in science. But two years later, the funds ran out. The Mauna Loa Observatory was forced to close. Keeling traveled to Washington, D.C., and was able to persuade NSF to resume funding. By 1964, Keeling's data were drifting upward. But it was difficult to regard this as a trend, rather than variation due to some natural cycle, say, in solar activity. Keeling had become aware of carbon dioxide as a greenhouse gas and its potential for warming the planet. He presented his data at a conference on the history of climate, but everyone seemed far more concerned about a sudden new Ice Age than any speculative increase in temperature in some remote future.

By the late 1960s, however, the trend of rising CO_2 was becoming unmistakable. After 10 years of data, the annual minimum had exceeded the first 1958 maximum. What no one could say definitively at the time was how the rise might affect global temperatures. For one, the oceans seemed likely to buffer any changes. Yet with public concerns about the environment on the rise, a Presidential advisory committee recommended that scientists continue to monitor carbon dioxide levels and study potential warming. The environmental significance of measuring CO_2 had become established.

But the recognition of its scientific importance hardly meant that funding was guaranteed. Over the next two decades, Keeling faced threatened shut downs of his measurement program again and again. First, a newly reorganized government agency started measuring CO_2 on its own, implying that it would replace Keeling's work. But Keeling did not trust the quality of their measurement techniques. Keeling continued. Then the NSF cast his work as "routine" and vowed to withhold further funding. So Keeling scrambled to find new ways to use the data, revealing new patterns related to tropical weather systems. The government, hoping to reduce costs, tried to institutionalize less stringent measurement methods. Whereupon Keeling rallied international support that firmly established his more rigorous standards. The government and NSF continued pressure to transfer the program. So Keeling found yet new ways to generate novel discoveries from the data, showing that carbon isotopes specifically implicated fossil fuels in the CO_2 increase. Keeling continued to worry that switching to poor-quality government measurements would invalidate long-term analyses of the data. Then, under the new presidency of Ronald Reagan, spending for environmental science was unilaterally cut. Congressional hearings by a junior congressman, Al Gore, however, helped raise public awareness of "global warming," and some funds were restored. Ultimately, Keeling managed to secure continuous funding from the Department of Energy. Over the course of three decades, however, Keeling had had to rely on at least nine sources of funding, most lasting only a few years. Given the challenges of funding and struggles over measurement standards, one might wonder how a long-term data set could have been built at all. That is was, ultimately, is largely a tribute to Keeling's perserverance and his political and scientific creativity. It is indeed fitting that we call the result the Keeling Curve.

○ Science, Backward & Forward

Thinking backward from today's Keeling Curve, one might easily imagine that Keeling had some special genius in knowing how his measurements would be meaningful decades later. If one views science as a methodical unfolding of inventing and testing theories, this may seem the only answer. Keeling seems a visionary, "ahead of the curve" as the saying goes.

Biologists might take an interpretive clue from evolutonary history. Evolution, we know, is non-teleological. Natural selection acts on adaptive features in the moment, not in an imagined future. Just because lightweight feathers are integral to flight now does not mean that they originated for this function. They insulated dinosaurs, long before the prospect of flying. Likewise, lungs made the vertebrate transition to land possible. But first, as swim bladders, they helped regulate buoyancy in organisms that were thoroughly aquatic. Ears enable all sorts of behaviors associated with sounds, from escaping predators to finding mates with exotic calls. But ears are remnants, in a sense, of the lateral line organ in fish, which detects nearby movement in the water. Contexts change. Functions transform. Current function can betray the history.

We need to conceive evolution as a process from the perspective of the past, proceeding forward.

So, too, with human endeavors and science. One would be mistaken to think that because he "discovered" America for Europeans, with the subsequent migrations and momentous displacements of populations and culture, Columbus had forseen or intended this originally. Science, too, inches forward, somewhat blindly perhaps, depending on chance and unexpected contingency more than is commonly acknowledged. Educators might reflect on the special set of skills that students might learn for transforming vague opportunity into concrete discovery. Ultimately, it is not possible to be "ahead of one's time." Keeling's recognition is well earned, but not for early insight into an improbable future. Following the history of the Keeling Curve looking forward shows well how contexts can shift and observations can be fortuitously recontextualized.

The very phrase "ahead of the curve" has its own ironic history (Quinion, 2011). Nowadays, it has come to share a meaning with "ahead of the game" or "ahead of the pack," in the sense that in retrospect someone seems to exhibit leadership by having anticipated uncertain or unknown future events. For some, the "curve" is the Bell Curve. There, "ahead of the curve" means rare, exceptional performance, as in "head of the class." But the phrase originated in aviation. Airplanes deal with both lift and drag, each based on airspeed. The relationship between airspeed and drag, marking the transition between flying and falling, is known as the power curve. To maintain control of the aircraft, a pilot wants to remain "ahead of the power curve." Some time in the 1970s, apparently, the phrase jumped, through military analogy, into political contexts where administrators wanted to maintain control and "navigate" securely as the public reacted to adverse news. Now, the history of the phrase is, well, history. And we blithely forge ahead, imagining on occasion that someone like Keeling might be "ahead of the curve." History – and the process of science – looks different, backward and forward.

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The nature of science lessons in the history of the Keeling Curve are nicely rendered in a guided-inquiry case study, "Charles Keeling & Measuring Atmospheric CO_2*," from which this essay draws (Leaf, 2011).*

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DOUGLAS ALLCHIN has taught both high school and college biology and now teaches history and philosophy of science at the University of Minnesota, Minneapolis, MN 55455; e-mail: allchin@sacredbovines.net. He is a Fellow at the Minnesota Center for the Philosophy of Science and edits the SHiPS Resource Center (ships.umn.edu). He hikes, photographs lichen, and enjoys tea.