a scholar in a study, but an avid experimentalist—one who philosophized about invisible entities only when experiments took him no further. In fact, in the course of researching the paper, Jed himself seems to turn into a sort of Californian Descartes: hanging water-filled spheres from the balcony of his Altadena home and fiddling around with prisms in the living room. Then, there is Jed's beautiful paper "Discrepant Measurements" (*Buchwald 2007a*). Aside from the remarkable discovery that Newton averaged out the values within large sets of data, Jed unexpectedly shows us that the telescope of a Robert Hooke was no more accurate than the eye of a Johannes Hevelius. Jed takes his history seriously: will the machine-eye replace the human? As academia moves to digital methods, Jed makes his case not for the abstraction of the algorithm, but "the scholar's seeing eye."

Jed Zachary Buchwald is an unforgettable presence in the history of science. With an eye for technical details and a vision for conceptual shifts, he has illuminated past science in both theory and practice. I am deeply indebted to him: for his insights and his inspiration.

Jesse H. Ausubel

Microphysics and Macrohistory

The microphysics of butterflies causes history. So does the leadership of great women. Others attribute history-making to the deadly sins catalogued by Thomas Aquinas in the 13th century—wrath, greed, pride, envy, lust, gluttony, and sloth. Christopher Marlowe wrote unforgettably in 1594 that Helen's face launched a thousand ships. Others say that the cardinal virtues, mainly justice and courage, are the prime movers.

No matter what we choose as our prime human historical mover, we have to understand that strong existential limitations greatly reduce the freedom of strategists, whether farmers, scientists, or generals, whether a family, corporation, or nation. In a century so far glorifying the power of human decisions, let us not forget fate.

Let me begin with a doctrine from American history known as Manifest Destiny. The term, first used in 1845 by a journalist, referred to the inevitably continuing westward territorial expansion of the United States through conquest and purchase—or, I would say, diffusion. Maps which all American students saw on classroom walls showed the major spatial changes, encompassing the transition from colonial settlements with foot paths into the forests to a nation integrated by transcontinental railways, interstate highways, gas pipelines, and electricity grids (figure 1).

Figure 1. National Atlas map (circa 2005) depicting U.S. territorial acquisitions. Source: National Atlas of the United States, Department of the Interior.

In a study of the quantitative history of twenty human empires, Cesare Marchetti and I plotted the areal growth of the USA as analogous to the growth in height of a sunflower (figure 2).[1] The fit is beautiful, over 250 years—through wars, depressions, epidemics, and other disturbances.

So no matter what the results of their agency and individual actions may have been, Thomas Jefferson and Lewis & Clark and Sacajawea and so on were also actors in a play. Most people, whether generals or bandits, like to believe they are decision makers, not the blind executors of a blind but all-powerful fate. Greek mythology helps us to understand the problem with this kind of thinking. Because although all gods reported to Zeus, *tuchē*, or fate—abstract, invisible, and

1. C. Marchetti, J. H. Ausubel. Quantitative Dynamics of Human Empires. Adapted from Marchetti and Ausubel, *International Journal of Anthropology* 27(1-2):1–62, 2012. 2013.

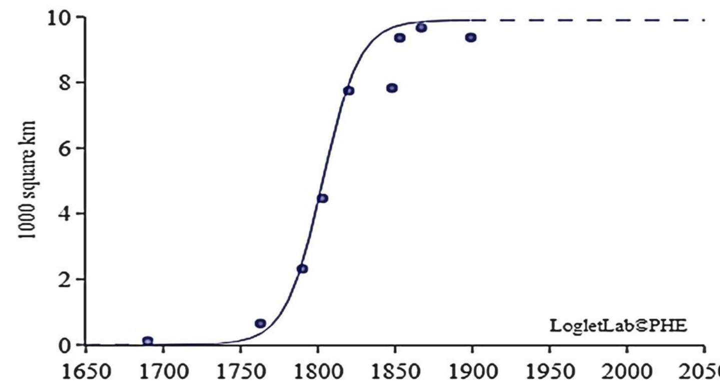

Figure 2. Spatial trajectory of the Roman Empire. Source: Marchetti and Ausubel, 2013, p. 13.

all-pervasive—ran the system, Zeus included. Americans—and scholars everywhere—still have much to learn from the ancient Greeks.

Let me introduce a general concept about how systems grow and evolve. Systems grow by substitution, by mutation and selection. Evolution is a series of replacements. An innovation, a mutation, enters the picture and if it is fitter for the task, it gains a growing and often obliviating share of its ecological niche or market. Often the substitution process follows an s-shaped curve, both in taking over a niche and in subsequently losing it.[2] A familiar example is recording media, where tapes overtook long-playing records, and in turn CDs replaced tapes, and MP3s and systems of downloading and streaming have now overtaken CDs (figure 3). In addition, the superior competitor often spurs system usage to grow.

2. P. S. Meyer, J. W. Yung, J. H. Ausubel. "A primer on logistic growth and substitution: The mathematics of the Loglet Lab software." *Technological Forecasting and Social Change* 61(3): 247–271, 1999.

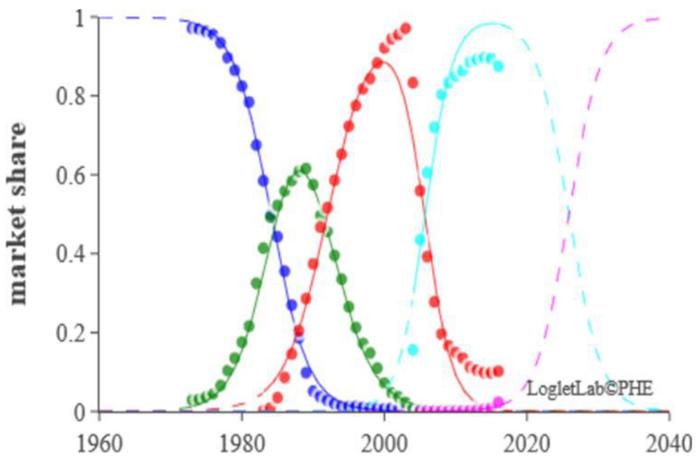

Figure 3. Substitution of recording media in the US market. Media are records or vinyl (dark blue), cassettes or tape (green), CDs (red), downloads (light blue), and paid subscriptions or streaming (purple). Plotted by Perrin Meyer and David Burg. Data available at https://logletlab.com/?page=index&preload=library.get.1

Consider a substitution process from the said-to-be free-for-all world of high technology and venture capital. Eight generations of sales of Dynamic Random Access Memory (DRAM) chips increase in Prussianesque order from 1973 to 2000 (figure 4).[3]

Another—in this case grim but elegant example of substitution—comes from the causes listed on death certificates. Think of causes of death such as heart attacks, cancer, and infections as competitors for corpses, a market that we all seek to shrink. Charts we plotted twenty years ago found an orderly evolution in America during the seemingly disorderly 20th century and thus allowed us to predict that cancer would become the number one

3. N. M. Victor, J. H. Ausubel. "DRAMs as a model organism for study for technological evolution." *Technological Forecasting and Social Change* 69(3): 243–262, 2002.

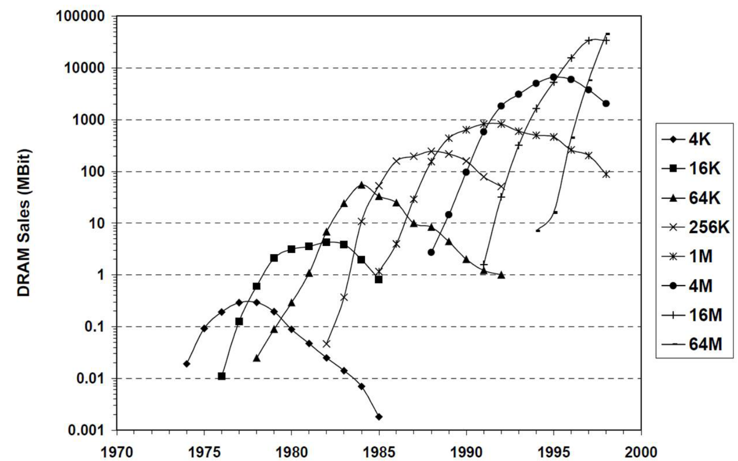

Figure 4. Logistic substitution of sales of Dynamic Random Access Memory chips. *Victor and Ausubel 2002*.

cause of death by about 2020 (figure 5).[4] America is fulfilling this destiny, too. Only the fittest causes of death survive.

These four examples span the Louisiana Purchase, presidents and generals, turnpikes, railroads, and telegraphs; corporations such as RCA and KLH, phonographs, magnetic tape, and optical disks; and personalities from Thomas Edison to Steve Jobs; inventions and patents at the IBM Watson Lab and then ferocious competition by Intel and other players in the silicon game, in Taiwan and Japan too; and a great flu pandemic, sewage treatment, vaccines, and hundreds of drugs and millions of surgeries. They embrace countless lawsuits, regulations, mischief, crimes and conspiracies, janitors and billionaires.

Let me add one more—environmentally crucial—example from primary energy, where human behavior has managed to defy the script for three decades or so after long, faithful

4. J. H. Ausubel, P. S. Meyer, I. K. Wernick. "Death and the human environment: The United States in the 20th century." *Technology in Society* 23(2): 131–146, 2001

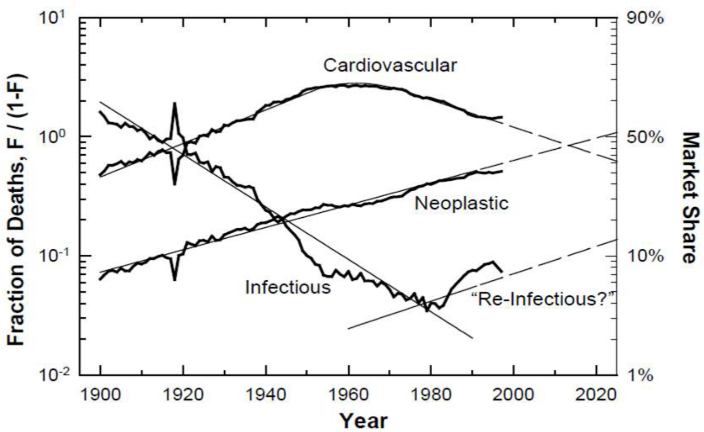

Figure 5. Competition for corpses among major causes of USA deaths during the 20th century, plotted on semi-log scale (normalized to one hundred percent of the market). Dashed lines show a fit with the logistic substitution model, including a forecast. *Ausubel, Meyer, and Wernick 2001.*

repetition. For about 150 years, until about 1990, the substitution of hydrogen for carbon in the energy system, and from wood and hay, to coal, to oil, to gas, and the resulting decarbonization, beautifully described the ongoing energy transition (figure 6).[5]

The explanation for this long-term pattern is simple. The evolution of the system is driven largely by the increasing spatial density of energy consumption at the level of the end user, that is, the energy consumed per square meter, for example, in a city. As high-rise urbanization lifts spatial density of energy consumption, fuels must conform to what the end user will accept, and constraints become more stringent. Rich, tall, dense cities accept happily only electricity and natural gas, and, incipiently, hydrogen.

5. J. H. Ausubel. "Where is energy going?" *The Industrial Physicist* 6(1): 16–19, 2000.

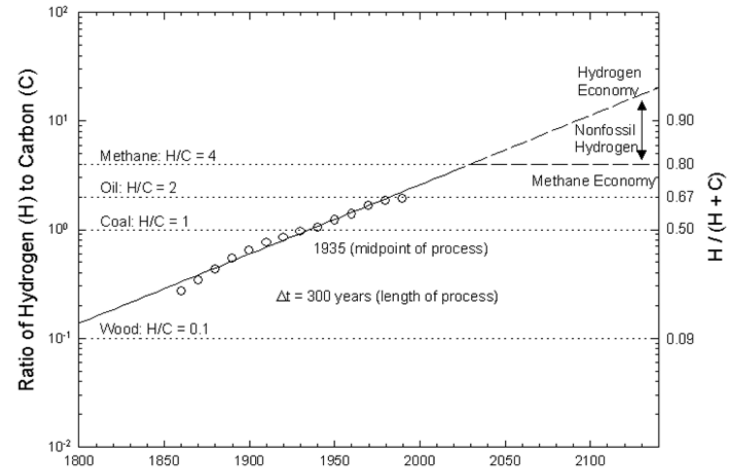

Figure 6. Decarbonization of the global energy system measured as the ratio of hydrogen atoms to hydrogen + carbon atoms in primary energy sources. "Policy' appears to have deferred decarbonization by about a generation. *Ausubel 2017.*

About a generation ago, humans managed to stall decarbonization through a series of incredibly contrived energy policies favoring the evolutionarily unfit. Had the energy system not become so self-conscious, it would probably be far closer to its low-carbon destiny today. In the energy system, reflexivity has mobilized interest groups whose interactions have favored the *status quo*. But finally, after many rationalizations, clean supply systems that benefit from economies of scale will produce the lion's share of the electricity and gases we will need. If you might dismiss scale, think of Facebook, Amazon, and Google, or Samsung and Alibaba. In a society of flash trading and flash mobs, perfect power—that is, ultra-reliable electricity—also wins in the Darwinian game.

In the case of the USA, the script for energy supply is simply to favor natural gas (with some carbon capture and sequestration), nuclear, and hydrogen.[6] Although few have noticed, USA hydrogen production is climbing nicely. And fuel cells, engines on hydrogen, will greatly increase their market, as wise automakers understand. On the demand side, we naturally seek to raise the rates of efficiency gain, to shrink usage, to decouple energy from GDP and carbon from BTU. A key is to focus on systems and practices with big upsides, such as the share economy which can lift capital utilization, and magnetically levitated trains and other vehicles which carry neither engine nor fuel and thus weigh far less per kilo of passenger than traditional cars, trains, and planes. We can lessen the jack rabbit excursions around these ultimately inevitable trends often proposed and organized by politicians and stakeholders.

Historians traditionally view their subject as unfolding in an essentially random way, contingent upon the violent, retributive whims of a citizenry and the political machinations of a handful of influential individuals. But history is more accurately seen through a more deterministic lens in which it obeys its own internal logic, unbeknownst to those staffing the think-tanks or Sandinistas.

We feel a freedom of decision inside ourselves whose legitimacy economists and politicians assume as sacred dogma, in the face of the obvious determinism of many global or national outcomes such as Manifest Destiny. The situation fits the famous analogy between the somewhat free and unobservable behavior of single molecules and the beautifully clean relationship of pressure and volume in a gas on a macroscopic scale.

6. J. H. Ausubel. "Density: Key to Fake and True News About Energy and Environment." Presented at a meeting of the American Association of Petroleum Geologists, *Next 100 Years of Global Energy Use: Resources, Impacts and Economics*, Houston Convention Center, 4 April 2017. Published in AAPG's *Search and Discovery*, as contribution #70272, 28 June 2017.

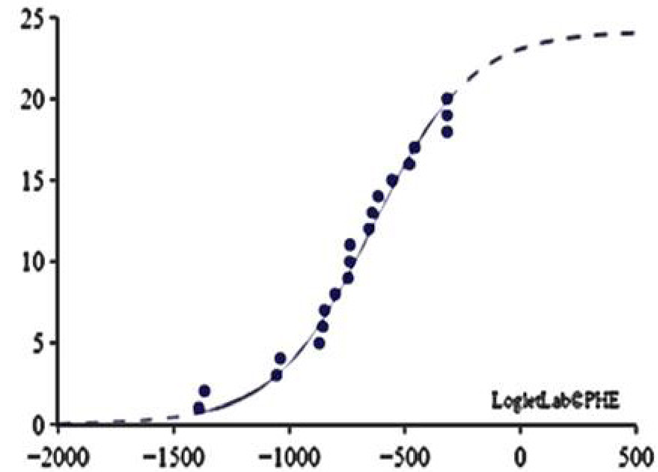

Figure 7. The writing of the Hebrew Bible charted as logistic growth process by the estimated birth dates of the authors. The process took 906 years to go from 10% to 90% completion, should have involved about 24 authors if fully realized, and reached its midpoint about 667 before the Christian era. *Wernick 2016.*

The determinism and feeling of liberty may not be contradictory. For example, the system requires the kamikaze behavior of entrepreneurs to evolve. But in the end we all feel the breath of fate. The writing of the Bible is a beautiful S-curve, accomplished by 24 authors over about 900 years (figure 7).[7]

Most of history, including the history of science and technology, is preprogrammed. Don't forget the system. It won't forget you.

Acknowledgements: Thanks to David Burg, Cesare Marchetti, Perrin Meyer, Nadejda Victor, and Iddo Wernick.

7. I. K. Wernick. "Jews in Time and Space." *International Journal of Anthropology* 31(1-2): 93–109, 2016.