

3

Cosmic Evolution – More Than Big History by Another Name

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Abstract

Evolution – ascent with change of Nature's many varied systems – has become a powerful unifying concept throughout the sciences. In its broadest sense, cosmic evolution, which includes the subject of big history, comprises a holistic explanatory narrative of countless changes within and among organized systems extending from the big bang to humankind. This interdisciplinary scenario has the potential to unite physical, biological, and social sciences, thereby creating for people of all cultures at the start of the new millennium a consistent, objective, and comprehensive worldview of material reality.

Historians

A few years ago, while having lunch in the Harvard Faculty Club with a group of science colleagues, I overheard a dispute among scholars at the table next to us. Several famous historians were squabbling about a frivolous territorial issue in their ancient and honorable discipline: Who studies history further back in time? The Greco-Roman expert maintained that the roots of his subject went way back, at least several thousand years. The Egyptian scholar argued that her studies involved events that were surely older, perhaps predating those of ancient Greece by a thousand years or more. And the Sumerian specialist tried to trump them all by claiming that his subject starts even earlier, maybe as long ago as 7000 years.

As they heatedly volleyed their arguments back and forth with growing indignation, I could not resist interrupting the historians – an intrusion they did not appreciate, for what right did I, as a scientist, have to say anything of use or interest to them. When I asserted, as an astrophysicist who looks out into space and thus back into time, that I was a 'real historian' whose studies extend into the past to nearly the beginning of time some 14,000,000,000 years ago, they became visibly upset. Their statements had been rendered nonsense, their subject matter reduced to minutia in the larger scheme of all history. At least one of those distinguished historians has not spoken to me since.

Big Historians

The recent onset of the new and exciting subject of big history has brought forth an outgoing and refreshing breed of historical scholars. Their stories are *Evolution: A Big History Perspective 2011 37–48*

inspiring, their outlook is uncommonly broad, and their attitudes open to new ideas, big ideas, indeed ideas central to fields well beyond their own. Big historians are helping to show that history writ large comprises many, diverse, yet related events that transpired well before those of recorded history, often extending back virtually to the beginning of time. This is not to say that I concur with all the words and assertions of the big historians. As a natural scientist, I often experience a mild reaction to their subjective inquiry, indeed I have been trained in quite different methods of scholarship that emphasize objectivity. My scientific work needs to be confirmed with empirical data, or at least be based on statements that are experimentally or observationally testable. Skepticism and validation are my central dogmas.

Nonetheless, it is easy for me to admire the emergence of Big History, whose practitioners are willing and able to cross disciplinary boundaries and whose subject name is simple, clear, and unpretentious. By studying past events that gave rise to humanity on Earth, indeed to Earth itself among the stars and galaxies, big historians naturally address Nature; to be sure, big history was once historically called just that – natural history, which is usually defined as ‘the study of natural objects and their evolution, origins, description, and interrelationships’. And since I have always regarded natural history expansively as a long and continuous narrative from the early Universe to the present time, not only incorporating the origin and evolution of a wide spectrum of systems and structures but also connecting many of them within an overarching intellectual framework, it is intuitive for me to relate favorably to their important work.

That said, even big historians' work is limited. Big History, as most often defined – ‘human history in its wider context’ (Christian 2004) or ‘an approach to history that places human history within the context of cosmic history’ (Spier 2010) – pertains mostly to the meandering cosmic trek that led specifically to us on Earth. As such, it mainly concerns, in reverse order of appearance, changes that led to humankind, the Earth, the Sun, and the Milky Way Galaxy. Scant treatment is given, or need be given, to other galaxies, stars, or planets throughout the almost unimaginably vast Universe, for the goal of Big History is to place humanity itself into a larger cosmic perspective. Furthermore, big historians especially need not be burdened with claims of multiple universes on macro-scales unimaginably larger than even those conceived by most physicists today, or of string theory and extra dimensions on micro-scales fully twenty orders of magnitude smaller than anything we can now measure – least of all that we and everything around us are cyberspace avatars in an alien computer simulation running an infinity of parallel worlds and implying that all possible histories conceivable are occurring somewhere, and maybe even everywhere an infinite number of times – none of which mathematical notions currently have any empirically supporting evidence whatsoever (Penrose 2010; Greene 2011).

In declaring these caveats, I wish neither to belittle Big History nor to critique those colleagues who prefer to speculate about the life and times of meta-events beyond the confines of our 14-billion-year-old Universe. Rather, I seek to make clear that most natural scientists still embrace the definition that ‘the Uni-

verse is all that there is: the totality of all known or supposed objects and phenomena, formerly existing, now present, or to come, taken as a whole', and to suggest that if big historians are to make headway, indeed to be accepted by traditional historians, they ought to ground their research agenda on empirical facts and tested ideas, where possible, and to focus their subject matter on the role of humanity in the one and only Universe we know.

Cosmic Evolution

Big History is not new, although one might not realize it by reading its current (March 2011) Wikipedia entry; the impression given is that this subject was invented hardly 20 years ago by traditional historians who began realizing that history actually reached well back beyond the onset of civilization. Broad, interdisciplinary explications of natural history have been researched and taught by natural philosophers since Renaissance times, and the specific big-bang-to-humankind story of special interest to big historians has been championed in recent decades largely by cosmologists, who arguably think more broadly than anyone else on Earth. It is the latter astronomers, who in modern times have christened their subject 'cosmic evolution', but which is alternatively known within various academic disciplines as macroevolution, universal history, and the epic of evolution. (My original, qualitative book exposition Chaisson 1981, was updated in 2006 and made quantitative in 2001; a recent readable summary and a technical review can be found at 2009a and 2009b, respectively – all referenced at the end of this paper.¹)

Cosmic evolution is the study of the sum total of the many varied developmental and generational changes in the assembly and composition of radiation, matter, and life throughout the history of the Universe. These are the physical, biological, and cultural changes that have generally produced galaxies, stars, planets, and life-forms – specifically, regarding Big History and its more limited coverage, the Milky Way, Sun, Earth, and life on our planet, especially human life. The result is an inclusive evolutionary synthesis bridging a wide variety of scientific specialties – physics, astronomy, geology, chemistry, biology, and anthropology – a genuine scientific narrative of epic proportions extending from the beginning of time to the present, from the big bang to humankind.

Nor is the general study of change itself new; its essence extends back at least 25 centuries when the philosopher Heraclitus arguably made the best observation ever while noting that 'everything flows ... nothing stays'. This remarkably simple idea is now essentially confirmed by modern scientific reasoning and much supporting data – indeed the notion that change is ubiquitous in Nature is at the heart of cosmic evolution. Other researchers have addressed life and complexity in a cosmic setting, among them Chambers (1844), who anonymously wrote a pre-Darwinian tome of wide interdisciplinary insight, and

¹ Most of my recent journal publications including those in the Reference can be downloaded from my research page: http://www.tufts.edu/as/wright_center/eric/ericrsrch.html.

Shapley (1930), who pioneered ‘cosmography’ that classified all known structures according to increasing dimensions. Spencer (1896) also broached the idea of growing complexity in biological and cultural evolution, Henderson (1913) regarded the whole evolutionary process, both physical and biological, as one and the same, Whitehead (1925) sought to broaden scientific thinking with his ‘organic philosophy’, von Bertalanffy (1968) championed a systems theoretic approach to physical, biological, and social studies, and Shklovskii and Sagan (1966) popularized the idea of intelligent life in the cosmos. Later in the 20th century, several independent efforts came forth virtually simultaneously, as Sagan (1980), Jantsch (1980), Reeves (1981), and Chaisson (1981) all advanced the idea of complex systems naturally emerging with the pace of natural history.

Fig. 1 sketches Nature's different kinds of evolution atop the so-called ‘arrow of time’. These three evolutionary subsets constitute the whole of cosmic evolution: physical evolution → biological evolution → cultural evolution, each describing how, in turn, ‘islands’ of growing complexity emerged to become ordered systems, whether massive stars, colorful flowers, or busy cities. Regardless of its shape or orientation, such an arrow symbolizes the *sequence* of events that have changed systems from simplicity to complexity, from inorganic to organic, from chaos in the early Universe to order more recently. That sequence accords well with a long and impressive chain of knowledge linking seven major epochs in time – particulate, galactic, stellar, planetary, chemical, biological, and cultural – wherein each changed chronologically:

- elementary particles into atoms,
- atoms into galaxies and stars,
- stars into heavy elements,
- elements into organic molecules,
- molecules into life,
- life into intelligence,
- intelligence into cultured and technological civilization.

Despite the extreme specialization of modern science, evolution marks no disciplinary boundaries; cosmic evolution is a truly interdisciplinary topic. Accordingly, the most familiar kind of evolution – biological evolution, or neo-Darwinism – is just one, albeit important, subset of a broader evolutionary scenario stretching across all of space and all of time. In short, what Darwinian change does for plants and animals, cosmic evolution aspires to do for all things. And if Darwinism created a revolution in understanding by helping to free us from the anthropocentric belief that humans differ from other life-forms on our planet, then cosmic evolution extends that intellectual revolution by treating matter on Earth and in our bodies no differently from that in the stars and galaxies far beyond.

Anthropocentrism is neither intended nor implied by the arrow of time; the arrow is not pointing at humankind. Anthropic principles notwithstanding, no logic supports the idea that the Universe was conceived in order to produce specifically us. Humans are not the pinnacle or culmination of the cosmic-

evolutionary scenario, nor are we likely the only technologically competent beings that have emerged in the organically rich Universe. The arrow merely provides an archetypal symbol, artistically conveying the creation of increasingly complex structures, from spiral galaxies to rocky planets to thinking beings.

Note, finally, that time's arrow does not imply that primitive, 'lower' life-forms have biologically changed directly into advanced, 'higher' organisms, any more than galaxies have physically changed into stars, or stars into planets. Rather, with time – much time – the environmental conditions suitable for spawning simple life eventually changed into those favoring the biological origin and evolution of more complex species. Likewise, in the earlier Universe, the physical evolution of environments ripe for galactic formation eventually gave way more recently to conditions conducive to stellar and planetary formation. And now, at least on Earth, cultural evolution dominates, since our local biospheric environment has once more changed to foster robust, societal complexity. Change in surrounding environments usually precedes change in organized systems, and the resulting changes for those systems selected to endure in Nature have *generally* been toward greater amounts of diverse order and inherent complexity.

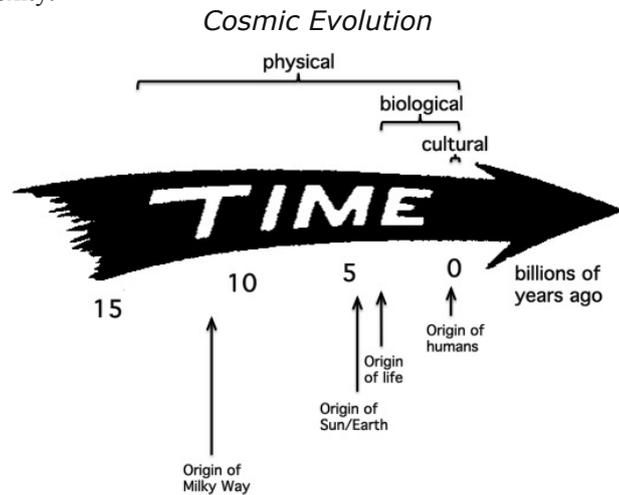


Fig. 1. An arrow of time symbolically chronicles the principal epochs of cosmic history, from the beginning of the Universe ~14 billion years ago (at left) to the present (at right). Labeled across the top are three major types of evolution (physical, biological, and cultural) that have produced, in turn, increasing amounts of order and complexity among material systems observed in the Universe. Cosmic evolution, as a general and inclusive term, comprises all of these subset evolutionary types and temporal phases

Energy Flows and Complexity Rises

Of special interest to big historians are the origin and evolution of the many diverse systems spanning the Universe today, notably those that sequentially and eventually gave rise to humanity on Earth. Particularly intriguing is the increase in complexity of those systems over the course of time, indeed dramatically so (with some exceptions) within the past half-billion years since the Cambrian period on our planet. Both theory and experiment, as well as computer modeling, suggest that islands of increasingly ordered complexity – namely, open, non-equilibrium systems that mainly include galaxies, stars, planets, and life-forms – are numerically more than balanced by great seas of growing disorder elsewhere in the environments beyond those systems. All emergent systems engaged in the cosmic-evolutionary scenario agree quantitatively with the valued principles of thermodynamics, especially its entropy-based 2nd law (Chaisson 2001). Yet what has caused the emergence of systems and their rise in complexity over time, from the early Universe to the present? Is there an underlying principle, general law, or ongoing process that creates, organizes, and maintains all complex structures in the Universe?

Briefly stated and while keeping technicality minimized, I have suggested for at least a quarter-century that energy flows are at the heart of the cosmic-evolutionary story (Chaisson 1987, 2001, 2004). In particular, specific energy flow (*i.e.* energy rate per unit mass) constitutes a useful complexity metric and potential evolutionary driver for all constructive events throughout universal history. Energy does seem to be a common currency among all such ordered structures; whether living or not, all complex systems acquire, store, and express energy. Energy flow may well be the most unifying process in all of science, helping to provide a cogent explanation for the onset, existence, and complexification of a whole array of systems – notably, how they emerge, mature, and terminate during individual lifetimes as well as across multiple generations.

The chosen metric, however, can be neither energy alone nor even merely energy flow. Life on Earth is surely more complex than any star or galaxy, yet the latter utilize much more total energy than anything now alive on our planet. Accordingly, I have normalized energy flows in complex systems by their inherent mass, thus better enabling more uniform analysis while allowing effective comparison between and among virtually every kind of system encountered in Nature. This, then, has been and continues to be my principal working hypothesis in cosmic evolution: mass-normalized energy flow, termed energy rate density and denoted by Φ_m , is possibly the most universal process capable of building structures, evolving systems, and creating complexity throughout the Universe (Chaisson 2003).

Fig. 2 summarizes much recent research on this subject (Chaisson 2010, 2011), depicting how physical, biological, and cultural evolution over ~14 billion years have changed simple primordial matter into increasingly intricate and complex structures. (For specific power units of W/kg, divide by 10^4 .) Values plotted are typical for the general category to which each system belongs, yet as with any eclectic, unifying theme in an imperfect Universe – especially one like cosmic evolution that aspires to address all of Nature – there are variations. And it is likely that from those variations arose the great diversity among complex, evolving systems everywhere.

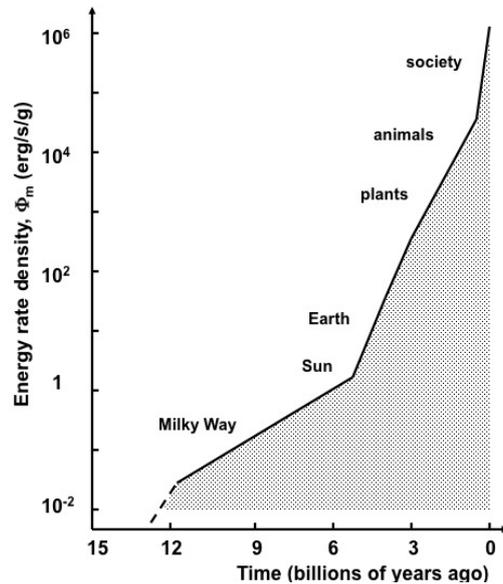


Fig. 2. Energy rate densities, Φ_m , for some complex systems of special interest to big historians, plotted here semi-logarithmically at the time of their origin, display a clear increase during the ~14 billion-year history of the Universe. The shaded area includes an immense array of changing Φ_m values as myriad systems evolved and complexified (data are from Chaisson 2010, 2011, and 2012)

Following the graphed trend in Fig. 2, which addresses complex systems of greatest interest to big historians concerned with the specific evolutionary path that likely led to our human society, I have found systematic increases in the energy rate density (expressed here in the metric units of erg/s/g, evaluated against time in billions, millions, and thousands of years ago, Gya, Mya, and kya, respectively).

Within physical evolution:

- The Milky Way Galaxy evolved from protogalactic blobs > 12 Gya ($\Phi_m \approx 10^{-3}$ erg/s/g), which became widespread dwarf galaxies ($\sim 10^{-2}$), then a mature, normal galaxy ~ 10 Gya (~ 0.05), and currently our galaxy's present state (~ 0.1).

- The Sun evolved from a protostar ~ 5 Gya ($\Phi_m \approx 1$ erg/s/g) to become a main-sequence star currently (~ 2), and will continue evolving to subgiant status ~ 6 Gya in the future (~ 4), eventually terminating as an aged red-giant star ($\sim 10^2$).

Within biological evolution:

- Plants evolved from microscopic protists > 470 Mya ($\Phi_m \approx 10^3$ erg/s/g), to seedy gymnosperms ~ 350 Mya ($\sim 5 \times 10^3$), to flowering angiosperms ~ 125 Mya ($\sim 7 \times 10^3$), and to highly efficient C_4 plants ~ 30 Mya ($\sim 10^4$).

- Animals evolved from fish and amphibians 370–500 Mya ($\Phi_m \approx 4 \times 10^3$), to cold-blooded reptiles ~ 320 Mya ($\sim 3 \times 10^3$), to warm-blooded mammals ~ 200 Mya ($\sim 4 \times 10^4$), and to flying birds ~ 125 Mya ($\sim 9 \times 10^4$).

Within cultural evolution:

- Human society evolved from hunter-gatherers ~ 300 kya ($\Phi_m \approx 4 \times 10^4$ erg/s/g), to agriculturists ~ 10 kya ($\sim 10^5$), to industrialists ~ 200 ya ($\sim 5 \times 10^5$), and to technologists of today ($\sim 2 \times 10^6$).

- Machines evolved from primitive devices ~ 150 ya ($\Phi_m \approx 10^5$ erg/s/g), to the invention of automobiles ~ 100 ya ($\sim 10^6$), to the development of airplanes ~ 50 ya ($\sim 10^7$), and to modern jet aircraft and their computers ($\sim 5 \times 10^7$).

Or, for those readers who prefer words devoid of numbers, a simple ‘translation’ of the above technical summary suggests a ranked order of increasingly complex systems across the many successive phases of cosmic evolution:

- mature galaxies are more complex than their dwarf predecessors;
- red-giant stars are more complex than their main-sequence counterparts;
- eukaryotes are more complex than prokaryotes;
- plants are more complex than protists;
- animals are more complex than plants;
- mammals are more complex than reptiles;
- brains are more complex than bodies;
- society is more complex than individual humans;
- machines are more complex than societies.

Better metrics than energy rate density may well describe each of the system categories within the more restricted domains of physical, biological, and cultural evolution that combine to create the greater whole of cosmic evolution, but no other single metric seems capable of uniformly describing them all. The significance of plotting on a single graph one quantity for such an enormously wide range of systems observed in Nature should not be overlooked.

I am unaware of any other single quantity (Φ_m) that can characterize so extensively and uniformly so many varied complex systems spanning ~ 20 orders of magnitude in spatial dimension and nearly as many in time.

What seems inherently attractive is that energy flow as a universal process helps suppress entropy within increasingly ordered, localized systems evolving amidst increasingly disordered, wider environments, indeed a process that arguably governed the emergence and maturity of our galaxy, our star, our planet, and ourselves. If correct, energy itself is the mechanism of change in the expanding Universe. And energy rate density is an unambiguous, objective measure of energy flow enabling us to gauge all complex systems in like manner, as well as to examine how over the course of time some systems evolved to command energy and survive, while others apparently could not and did not. The optimization of such energy flows might well act as the motor of evolution broadly conceived, thereby affecting each of cosmic evolution's subset domains of physical, biological, and cultural evolution.

Teaching Cosmic Evolution

My philosophy of approach firmly grounds my research in empiricism, mines data from a wealth of observations, and aims to synthesize history in a seamless story that unifies much of what is actually known to exist in Nature. Fig. 2 contains a huge amount of data, computations, and modeling, summarizing many years of effort to interpret, at a quantitative level, my original exposition of the modern cosmic-evolutionary scenario (Chaisson 1981). Cosmic evolution has become a natural way for me to cross stultifying academic boundaries and to understand – at some level, in chronological order, and in a unified way – many of the complex, organized systems in the known Universe. To be honest, it has been a personal intellectual journey to learn about who I am and whence I came.

My interests in interdisciplinary science are deeply rooted in my earlier career, extending back several decades when I first arrived as a student at Harvard. It was then that I aimed to enroll in the course that I had always wanted to take, but found that it did not exist. I was seeking a broad survey course that cut across the boundaries of all the natural sciences, not only because I was unsure which of the sciences I might like later to study in depth but also because I was personally seeking an overarching, integrated worldview. I was eager to make sense of all that I saw around me in the air, land, sea, and sky, and I was especially struggling to place myself into the big picture of Nature writ large.

Sadly, nearly everyone I met 40 years ago – much as still the case today – was into 'their own thing'. Peers studied narrow disciplines, faculty researched specialized domains, and few people showed much interest in others' fields of knowledge. That universities are so lacking in universal learning and teaching was my biggest disappointment at the time, and still is. There had been a few

earlier exceptions: Observatory director Harlow Shapley had taught a wide survey on ‘cosmography’ from the 1920s to the 1950s, and (my predecessor) Carl Sagan had taught ‘life in the universe’ to big crowds in the 1960s; but by the time I arrived as a student, Shapley was dead, Sagan banished, and the broad course I sought was nowhere to be found in the Harvard curriculum.

Less than a decade later, when I was appointed to the Harvard faculty in the mid-1970s, I was fortunate to be able to co-(re)create that broad survey course along with a senior professor, George Field, who had also long wanted to teach the sciences in integrated fashion. We called the course ‘cosmic evolution’ and we resolved to make it intentionally ‘a mile wide and an inch deep’, regardless of expected criticism. This would be a true survey of the sciences from big bang to humankind – an interdisciplinary sweep across physics, astronomy, geology, chemistry and biology, with social studies included as well. We were unsure if any students would show up.

Within three years, Cosmic Evolution had become the largest science course on the Harvard campus, limited only by the fire codes of the biggest lecture hall. Its immediate acceptance and rapid growth were partly due to our having taken the art of teaching seriously, but mostly because students ‘voted with their feet’. When asked, the students were quick to reply that they, too, were seeking the bigger picture – trying to grasp a larger perspective of all else studied at college, and especially trying to create for themselves a grand system of understanding.

I have now taught cosmic evolution at Harvard for 28 of the past 35 years since its creation, almost all of those years (as now) alone. For the first few years, I imported many guest speakers, including Steve Jay Gould, E. O. Wilson, George Wald, and several other experts outside my own expertise of physical science. The guest talks were fine as individual appearances, but together they lacked educational continuity. So, when I received a Sloan Fellowship in the 1980s, I surprised my colleagues by using those funds to take a year's leave to learn for myself all the science needed to teach the epic myself. Solo teaching of the course has led to much greater satisfaction personally as it has forced me to keep abreast of advances in a wide spectrum of subject areas; and it has provided much richer pedagogy and continuity for attending students by having a single person present the bulk of the course content. This course's syllabus and multi-media web site are freely accessible: http://www.tufts.edu/as/wright_center/cosmic_evolution.

A few years ago, after many unsuccessful attempts to inaugurate a course in cosmic evolution at Tufts University (owing to the usual turf battles with specialized faculty members), I finally succeeded while co-conspiring with a senior scientist, David Walt, provided that the course was team-taught by representatives from each of the science departments. Today, ‘From the Big Bang to Humankind’ is a popular offering at Tufts, where I co-teach it with an organic

chemist, glacial geologist, developmental biologist, and cultural anthropologist. Such a team effort does lack educational continuity from speaker to speaker, but its decided advantage is that students meet a variety of leading researchers, each of whom has substantial expertise in their respective disciplines.

Our principal reason for creating this broad survey course at Tufts is that a distinct minority of students there studies natural science. Although about a third of incoming freshman each year indicates intent to major in math/science, less than 10 % graduate with a degree in it. It is not much different on many college campuses across the nation – Americans are opting out of science in droves. My contention has been – to the distress of many colleagues – that the science faculty is the main problem here. Blame need not be placed on elementary-school teachers or high-school curricula; rather, it is more likely that college professors, having shirked our duties to teach well, to teach broadly, indeed often to teach at all at the introductory level, have abrogated our responsibilities to disseminate the excitement and enthusiasm that we have for our subjects.

Even so, the hope was that such a survey that sweepingly integrates many science disciplines would renew student interest in science – and it most certainly has. The numbers are rising, the students once again voting with their feet. And they are very much inspired by the big picture, as witnessed this past semester when, after one of my lectures, a young woman paid me high tribute while remarking with tears in her eyes, ‘Thank you for helping me remember the love I once had for science’. That is the kind of sentiment that makes teaching this stuff for 35 years worthwhile!

Summary

The subject of cosmic evolution has been at the core of my entire academic career. It is the only thing I know – yet fortunately it includes vast facts, ideas, and implications. As I built the course at Harvard over decades (along with its extensive suite of online-supporting materials), my scholarly research agenda gradually shifted from mainstream astrophysics to fully embrace this interdisciplinary topic, and the science-education program that I direct at Tufts' Wright Center has adopted it as our intellectual theme. What started out as a search for a single course by a wandering student displaying hardly more than persistent curiosity became a life-long pursuit to understand our world, our universe, and ourselves.

Even after decades of researching, teaching, and writing about the epic of evolution, I am still unsure if I know who I am or how I really fit into the larger scheme of things. But I have found a lifetime of satisfaction exploring the general theme of cosmic evolution, publishing quantitative science to bolster the big-bang-to-humankind story, and especially sharing the details, excitement, and significance of that awesome story with countless people eager to discover their own worldviews. It has been, for me, the best of all scholarly

endeavors: I have selfishly sought to know myself, yet in the process I have apparently helped myriad others to explore themselves and their sense of place in the amazing cosmos.

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