COSMIC EVOLUTION

The Rise of Complexity in Nature

ERIC J. CHAISSON

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PREFACE

Using astronomical telescopes and biological microscopes, among a virtual arsenal of other tools of high technology, modern scientists are weaving a thread of understanding spanning the origin, existence, and destiny of all things. Now emerging is a unified scenario of the cosmos, including ourselves as sentient beings, based on the time-honored concept of change. From galaxies to snowflakes, from stars and planets to life itself, we are beginning to identify an underlying, ubiquitous pattern penetrating the fabric of all the natural sciences—a sweepingly encompassing view of the order and structure of every known class of object in our richly endowed Universe. We call this subject "cosmic evolution."[1]

Recent advances throughout the sciences suggest that all organized systems share generic phenomena characterizing their emergence, development, and evolution. Whether they are physical, biological, or cultural systems, certain similarities and homologies pervade evolving entities throughout an amazingly diverse Universe. How strong are the apparent continuities among Nature's historical epochs and how realistic is the quest for unification? To what extent might we broaden conventional evolutionary thinking, into both the pre-biological and post-biological domains? Is such an extension valid, merely metaphorical, or just plain confusing?

For many years, during the 1970s and 80s at Harvard University, I taught, initially with George B. Field, an introductory course on cosmic evolution that sought to identify common denominators bridging a wide variety of specialized science subjects—physics, astronomy, geology, chemistry, biology, and anthropology, among others. The principal aim of this interdisciplinary course explored a universal framework against which to address some of the most basic issues ever contemplated: the origin of matter and the origin of life, as well as how radiation, matter, and life interact and change with time. Our intention was to help sketch a grand evolutionary synthesis that would better enable us to understand who we are, whence we came, and how we fit into the overall scheme of things. In doing so, my students and I gained a broader, integrated knowledge of stars and galaxies, plants and animals, air, land, and sea. Of paramount import, we learned how the evident order and increasing complexity of the many varied, localized structures within the Universe in no way violate the principles of modern physics, which, prima facie, maintain that the Universe itself, globally and necessarily, becomes irreversibly and increasingly disordered.

Beginning in the late 1980s while on sabbatical leave at the Massachusetts Institute of Technology, and continuing for several years thereafter while on the faculty of the Space Telescope Science Institute at Johns Hopkins University, I occasionally offered an advanced version of the introductory course. This senior seminar attempted to raise substantially the quantitative aspects of the earlier course, to develop even deeper insights into the nature and role of change in Nature, and thus to elevate the subject of cosmic evolution to a level that scientists and lay persons alike might better appreciate. This brief and broadly brushed monograph—written mostly in the late 1990s during a stint as Phi Beta Kappa National Lecturer, and polished while resuming the teaching at Harvard of my original course on cosmic evolution—is an intentionally lean synopsis of the salient features of that more advanced effort.

Some will see this work as reductionistic, with its analytical approach to the understanding of all material things. Others will regard it as holistic, with its overarching theme of the whole exceeding the sum of Nature's many fragmented parts. In the spirit of complementarity, I offer this work as an evolutionary synthesis of both these methodologies, integrating the deconstructionism of the former and the constructivist tendencies of the latter. Openly admitted, my inspiration for writing this book has been Erwin Schrödinger's seminal little tract of a half-century ago, *What is Life?*, yet herein to straighten and extend the analysis to include all known manifestations of order and complexity in the Universe. No attempt is made to be comprehensive insofar as details are concerned; much meat has been left off the bones. Nor is this work meant to be technically rigorous; that will be addressed in a forthcoming opus. Rather, the intent here is to articulate a skeletal précis—a lengthy essay, really—of a truly voluminous subject in a distilled and readable manner. To bend a hackneyed cliché, although the individual trees are most assuredly an integral part of the forest, in this particular work the forest is of greater import. My aim is to avoid diverting the reader from the main lines of argument, to stay focused on target regarding the grand sweep of change from big bang to humankind.

Of special note, this is not a New Age book with mystical overtones however embraced or vulgarized by past scholars, nor one about the history and philosophy of antiquated views of Nature. It grants no speculation on the pseudo-science fringe about morphic fields or quantum vitalism or interfering deities all mysteriously affecting the ways and means of evolution; nor do we entertain epistemological discussions about the limits of human knowledge or post-modernist opinions about the sociological implications of science writ large. This is a book about mainstream science, pure and simple, outlining the essence of an ongoing research program admittedly multidisciplinary in character and colored by the modern scientific method's unavoidable mix of short-term subjectivity and long-term objectivity.

In writing this book, I have assumed an undergraduate knowledge of natural science, especially statistical and deterministic physics, since as we shall see, much as for classical biological evolution, both chance and necessity have roles to play in all evolving systems. The mathematical level includes that of integral calculus and differential equations, with a smattering of symbolism throughout; the units are those of the centimeter-gram-second (cgs) system, those most widely used by practitioners in the field. And although a degree of pedagogy has been included when these prerequisites are exceeded, some scientific language has been assumed. "The book of Nature is written in the language of mathematics," said one of my two intellectual heroes, Galileo Galilei, and so are parts of this one. Readers with unalterable math phobia will benefit from the unorthodox design of this work, wherein the "bookends" of Prologue-Introduction and Discussion-Epilogue, comprising more than half of the book, can be mastered without encountering much mathematics at all.

What is presented here, then, is merely a sketch of a developing research agenda, itself evolving, ordering, and complexifying—an abstract of scholarship-in-progress incorporating much data and many ideas from the entire spectrum of natural science, yet which attempts to surpass scientific popularizations (including some of my own) that avoid technical lingo, most numbers, and all mathematics. As such, this book should be of interest to most thinking people—active researchers receptive to an uncommonly broad view of science, sagacious students of many disciplines within and beyond science, the erudite public in search of themselves and a credible worldview—in short, anyone having a panoramic, persistent curiosity about the nature of the Universe and of our existence in it.

I thank those who read the penultimate draft of the manuscript, thereby saving me some embarrassing errors: Kate Brick, Larry Edwards, George Field, Dudley Herschbach, Jonathan Kenny, Hubert Reeves, Fred Spier, George Whitesides, and Rich Wolfson. Each of these distinguished specialists necessarily examined such an interdisciplinary work from a different perspective, and none of them can be expected to agree with all that remains—which is exactly the way that modern science seeks to discriminate sense from nonsense, selecting and accumulating the former at the expense of the latter and thereby moving us all toward a better approximation of reality.

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OVERVIEW OF COSMIC EVOLUTION

[We are] made of the same stuff of which events are made. . . The mind that is parallel with the laws of Nature will be in the current of events, and strong with their strength.

—Ralph Waldo Emerson, from the essay "Power" in *The Conduct of Life*

Since the dawn of civilization, men and women have wondered about, and even feared, the mysteries of the skies. At first, they approached their world subjectively, believing Earth to be the stable hub of the Universe, with Sun, Moon, and stars revolving about it. Stability led to a feeling of security, or at least contentment—a belief that the origin and destiny of the cosmos were governed by the supernatural.

With the advent of recorded history, our ancestors became aware of another mystery, namely, themselves. Indeed, the origin and destiny of human beings were as enigmatic as anything in the depths of space. Religions and philosophies held forth, providing grand myths, epic stories, and a genuine sense of well-being before an uncertain future.

Later, but only within the past few hundred years, humans began to adopt a more critical stance toward themselves and the Universe, seeking to view our world more objectively. With it, modern science was born, the first major product of which was the Copernican revolution. The idea of the centrality of Earth was demolished forever, and with it the false serenity that had been engendered by the unknown. Humankind came to feel that it was marooned on a tiny particle of dust drifting aimlessly through a hostile Universe.

More recent scientific developments, particularly within the past few decades, have continued to suggest that, as living creatures, we inhabit no unique place in the Universe at all. We live on what appears to be an ordinary rock called Earth, one planet orbiting an average star called the Sun, one stellar system near the edge of a huge collection of stars called the Milky Way, one galaxy among countless billions of others spread throughout the observable abyss called the Universe.

It is perhaps a sobering thought that we seem so inconsequential in the Universe. It is even more humbling at first—but then wonderfully enlightening—to recognize that evolutionary changes, operating over almost incomprehensible space and nearly inconceivable time, have given birth to everything seen around us. Scientists are now beginning to decipher how all known objects—from atoms to galaxies, from cells to brains, from people to society—are interrelated. We are attempting to sketch the unifying scenario of cosmic evolution, a powerful new epic for the new millennium.

Simply defined, cosmic evolution is the study of change—the vast number of developmental and generative changes that have accumulated during all time and across all space, from big bang to humankind. To quote some long-forgotten wit, "Hydrogen is a light, odorless gas which, given enough time, changes into people." More seriously and specifically, cosmic evolution comprises the sum total of all the many varied changes in the assembly and composition of radiation, matter, and life throughout the history of the Universe. These are the changes that have produced our Galaxy, our Sun, our Earth, and ourselves.

Tritely stated, though no less true, the word "evolution" implies neither dogmatism nor atheism. It harbors no premeditated, a priori implication for any religion or preferred philosophy of antiquity; there is no hidden agenda here. As used in this book, evolution is hardly more than a fancy word for change, especially, again, both developmental and generative change. The term itself derives from the Latin *evolvere,* meaning to unfold, to roll out. Indeed, it seems that change is the hallmark for the origin, maintenance, and fate of all things, animate or inanimate.

Change: To make different the form, nature, and content of something. Change has, over the course of time and throughout all space, brought forth, successively and successfully, galaxies, stars, planets, and life. Evidence for that change is literally everywhere. Whether we look out into the macroscopic realm with astronomical telescopes or down into the mesoscopic domain with biological microscopes or even sub-microscopically with high-energy accelerators, the most common feature perceived is change. Much of that change is subtle, such as when the Sun fuses sedately at mid-career for billions of years or when Earth's tectonic plates drift sluggishly across the face of our planet for equally long durations. By contrast, some of that change is much more dramatic, such as when very massive stars (unlike our Sun) perish catastrophically in supernova explosions or when geologic pressures amass near Earth's surface to cause sudden quakes and volcanoes.

Nothing seems immutable, nothing at all, much akin to the ancient philosophers' notion of "becoming" as a more genuine representation of existence. Indeed, Heraclitus of old may well have been right when he so cogently claimed some 25 centuries ago that there is nothing permanent except change. To emphasize the universality and interconnectedness of change, for everything in Nature seems related to everything else, a descriptive adjective from the Greek *kosmos,* meaning an orderly whole, does seem appropriate. We thus grant this process of "universal change" a more elegant, broad name—cosmic evolution—and we propose it as a majestic worldview that incorporates living beings quite naturally into the larger realm of all material things.

The Arrow of Time

Consider, as shown in Figure 1, the arrow of time—an archetypal illustration of cosmic evolution. Regardless of its shape or orientation, such an arrow represents an intellectual guide to the *sequence* of events that have changed systems from simplicity to complexity, from inorganic to organic, from chaos to order. That sequence, as determined from a substantial body of post-Renaissance observations, is galaxies first, then stars, followed by planets, and eventually life forms.[1] In particular, we can identify seven major construction phases in the history of the Universe (denoted diagonally in Figure 1): particulate, galactic, stellar, planetary, chemical, biological, and cultural evolution. These are the individual phases, separated by discontinuities from a myopic perspective, that demarcate the disciplinary and fragmented fields of today's specialized sciences.

As such, the most familiar kind of evolution—biological evolution, or neo-Darwinism—is just one subset of a much broader evolutionary scheme encompassing much more than mere life on Earth. In short, what Darwinism 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 notion that humans basically differ from other life forms on our planet, then cosmic evolution is destined to extend that intellectual revolution by releasing us from regarding matter on Earth and in our bodies any differently from that in the stars and galaxies beyond.

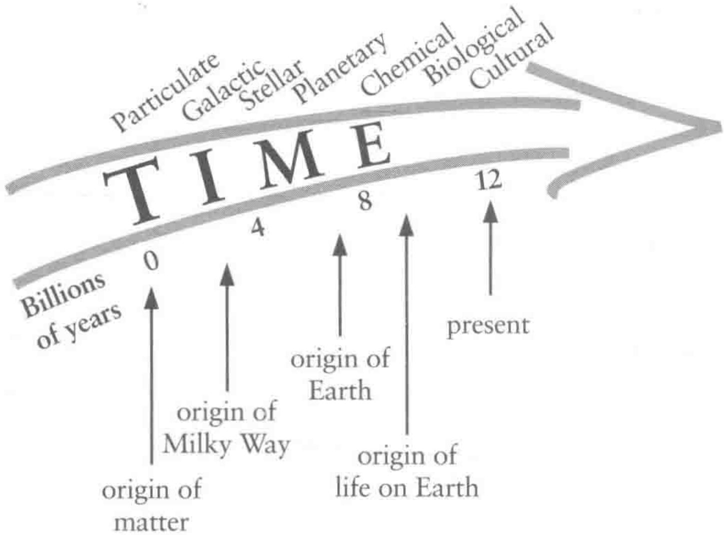

Figure 1. An arrow of time can be used to highlight salient features of cosmic history, from the beginning of the Universe to the present. Sketched diagonally along the top of this arrow are the major evolutionary phases that have acted, in turn, to yield increasing amounts of order and complexity among all material things. Despite its implication of "time marching on," the arrow is meant to imply nothing strictly deterministic, nor progressive. Much as for its most celebrated component—neo-Darwinism—the twin agents of chance and necessity embed all aspects of the cosmic-evolutionary scenario, whose temporal "arrow" hereby represents a convenient guide to natural history's many varied changes.

Of central importance, we can now trace a chain of knowledge—a loose continuity along an impressive hierarchy—linking the evolution of primal energy into elementary particles, the evolution of those particles into atoms, in turn of those atoms into galaxies and stars, the evolution of stars into heavy elements, the evolution of those elements into the molecular building blocks of life, of those molecules into life itself, of advanced life forms into intelligence, and of intelligent life into the cultured and technological civilization that we now share. These are the historical phases, much the same as those noted above but now reidentified from an integrated perspective, that comprise the interdisciplinary worldview of the present work. The attitude here is that, despite the compartmentalization of modern science, evolution knows no disciplinary boundaries.

Broadly conceived in this way, and despite its name, cosmic evolution is not confined to those changes within and among astronomical objects. Rather, this universal subject encompasses all change, on every spatial and temporal domain—large and small, near and far, past and future. Accordingly, neo-Darwinism becomes but one, albeit important, part of an extensive evolutionary scenario stretching across all of space and all of time.

Nor is cosmic evolution an attempt to extrapolate the core Darwinian principle of natural selection to realms beyond life forms. Ambitiously, it is more than that. Cosmic evolution is a search for principles that subsume, and even transcend, Darwinian selection—a unifying law, an underlying pattern, or an ongoing process perhaps, that creates, orders, and maintains all structure in the Universe, in short a search for a principle of cosmic selection.[2]

Metaphorically (at least), cosmic evolution aims to frame a heritage—a cosmic heritage—a grand structure of understanding rooted in events of the past, a sweeping intellectual map embraced by humans of the present, a virtual blueprint for survival along the arrow of time if our descendants of the future are to realize a future. The objective, boldly stated, is nothing less than a holistic cosmology in which life has not merely a place in the Universe, but also perhaps a significant role to play as well.

In effect, with cosmic evolution as the core, we espouse a new philosophy—a scientific philosophy. And we hasten to place due emphasis on that key adjective, "scientific." For unlike classical philosophy, observation and experimentation are vital features of this current effort; neither thought alone nor belief alone will ever make the unknown known. Cosmic evolution strives to address the fundamental and age-old questions that philosophers and theologians have traditionally asked, but to do so using the scientific method and its technological instruments—the most powerful twin techniques ever invented for the advancement of factual information.

Indeed, the same technology that threatens to doom us now stands ready to probe meaningfully some of the most basic questions ever asked: Who are we? Where did we come from? How did everything around us, on Earth and in the heavens, originate? What is the source of order, form, and structure characterizing all material things? How did (and does) order emerge from disorder, given that the second law of thermodynamics dictates the Universe to become increasingly randomized and unstructured? Can we reconcile the theoretical destructiveness of thermodynamics (often called the "thermodynamic arrow of time") with the observed constructiveness of cosmic evolution (the "cosmological arrow of time")? Of ultimate import, armed with a renewed and quantified perception of change, science now seems poised to address the origin of the primal energy at creation itself, and thus to tackle the fundamentally fundamental query: Why is there something rather than nothing?

However time flows and for how long, we take it to be a linear phenomenon, to unfold at a steady pace from its fiery origins to the here and now of the present. Likewise do we invoke the unchanging character of the physical laws (Feynman 1967), for without these assumptions we cannot meaningfully proceed to investigate our ancient past. These are also among the same assumptions underlying most studies of the far future (Dyson 1979), which is not a topic of this book; without unvarying constants of Nature and fixed principles of science, no objective advance can be made in understanding. All this is tantamount to saying that 2 + 2 = 4 throughout the Universe or that hydrogen atoms are built identically everywhere; if these central tenets are untrue, then read no further.

No Anthropocentric Agenda

Despite its clean and simple lines in Figure 1, the arrow of time harbors no implication of progression or directedness, no action that unhesitatingly and inevitably leads from the early Universe to ourselves. Anthropocentrism is neither implied nor intended by this arrow; no logic supports the idea that the Universe was conceived (or self-conceived) in order to produce us. We humans are surely not the culmination of the cosmic-evolutionary scenario, nor are we likely to be the only technologically sentient beings that have (or will have) emerged in the organically rich Universe. Flatly stated, there is here no veiled attempt, or hidden agenda, to exalt humankind or to place our species atop some elevated pedestal. As a philosophy of approach, and in keeping with empirical findings, the Copernican principle is in full force throughout this book, denying Sun, Earth, and life any special status—in time, in space, or in complexity.

Nor do we seek to resurrect the *scala natura*, or linear ladder of life, that ancient Aristotelian (or Hsun Ch'ing before him) stepwise hierarchy, or "great chain of being," of bygone pre-evolutionary days. "Lower," primitive organisms do not biologically change into "higher," advanced organisms, any more than galaxies physically change into stars, or stars into planets. Rather, with time—much time—the environmental conditions suitable for spawning primitive life forms eventually gave way to those favoring the emergence of more complex species; likewise, in the earlier Universe, the environment was ripe for galactic formation, but now those conditions are more conducive to stellar and planetary formation. Change in the surrounding environment usually precedes change in an organized system per se, and those system changes have *generally* been toward greater amounts of diversity and complexity. The popular image of a straight and narrow ladder of life itself evolved in Darwin's day into the metaphor of a branching treelike structure, with the simpler, mostly extinct and fossilized life forms comprising the thicker, bottom bulk of the tree, and the more complicated, currently living forms adorning its thinner limbs near the top. Nowadays, it is more common to imagine life's evolutionary model as a scrubby bush, or even a landscape of many stunted bushes amidst tall grasses and perhaps a few trees (Gould 1980).

The arrow of time in Figure 1 provides a simplified context for the rich natural history of all events that preceded us; it has worked well in classroom settings as a clear, compelling symbol. Even so, for those who would have trouble with such an innocent illustration in our cosmic-evolutionary lexicon, I offer Figure 2 as an alternative, perhaps less varnished rendering of events from the beginning of time to the present. If the thin, sleek arrow of Figure 1 is akin to a rather pruned tree of life, then the wider, yet cramped arrow of Figure 2 is analogous to the more realistic bush of life. Here, the dynamic tide of ceaseless change is portrayed in a more contorted fashion, the entire Universe resembling an intricate web of step-by-step causality. All the while, for either arrow, time is assumed to move linearly—granting evolution a partly random, undirected pace while building structures from spiral galaxies to barren planets to reproductive beings—though still sequentially, largely according to the structures' degree of complexity. Onward and upward? No, just onward; we cannot recapitulate enough that cosmic evolution entails no progress or design that equates humankind with the goal of some magisterial plan. Our deep-seated anti-anthropocentrism is one reason (the irreversibility of thermodynamics is another) that we prefer the symbol of a thickening, sideways-flowing arrow to any thinning, upward-thrusting ladder, tree, or bush.

Contingency—randomness, chance, stochasticity—pervades all of dynamic change on every spatial and temporal scale, an issue to which this book returns repeatedly. And with this uncertainty, we emphasize that science today is no longer in the prediction business, at least not nearly as much as in the older, Newtonian worldview; cosmic evolution predicts little of the future, yet strives to explain much of the past.

What about the anthropic principle, a nagging conundrum that just

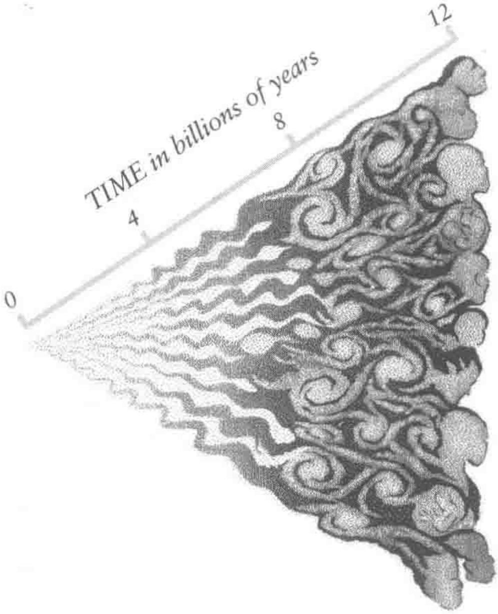

Figure 2. Time's arrow implies nothing anthropocentric. We humans are neither likely the pinnacle, nor surely the end product, of the cosmic evolutionary scenario. The shape of this figure—a more artistic, less diagrammatic "arrow" than in Figure 1—is meant to suggest that the number and diversity of structures have increased with time, yet without any kind of resemblance to a classical evolutionary tree having main trunks and well-defined branches. Whatever measure of complexity is used, it is hard to avoid the notion that "things"—whether galactic clouds, slimy invertebrates, luxury automobiles, or the whole Universe itself—have generally become more complicated throughout the course of history.

won't go away in cosmological circles (Carter 1974; Wald 1984; Barrow and Tipler 1986)? Stated in one of its many versions, "The Universe is the way it is because we are here to observe it." Or in another, "The Universe becomes knowable when there is someone to observe it." Or even, "We are here because the Universe is designed for us." All of these statements court anthropocentrism (as the principle's name implies) and, coincidences aside, a medieval purposive organization of matter—which is why the arguments of this book reject the anthropic principle's strong form, all the while accepting its weak form.

The issue is this: If the numerical values of certain physical constants (for example, the velocity of light, an electron's charge and mass, the gravitational constant, etc.) differed even slightly from their observed values, then the long sequence of events that produced galaxies, stars, planets, and life might have been impossible. The cosmos would likely be starless and lifeless, a proposition very much at odds with the one seen around us. A good example concerns the basic constant of gravity, $G = 6.67 \times 10^{-8}$ dyne-cm^2 g^{-2}: If G were much smaller, matter would not be able to compress enough to create the temperature and density needed for hydrogen ignition, hence stars would not have formed from dark balls of gas; if G were much larger, stars would have formed but would have burned hotter and endured for less time, making it improbable that life would have originated on any attendant planets. Another example is that if the foremost number in quantum mechanics—Planck's constant, $h = 6.63 \times 10^{-27}$ erg-s—were even a few percent larger or smaller, the nuclear reactions that create carbon in stars wouldn't work. Yet without carbon and the multiple bonding ability it confers on complex chemical structures, life as we know it couldn't exist. These hypotheticals suggest that there is a relatively small window of numerical values that would allow the existence of cosmos, stars, and life.

The "strong anthropic principle" implies that our Universe is very finely tuned—as if by fiat—in order to produce precisely certain kinds of structures that are observed, including, ultimately and inevitably, intelligent life. Those who subscribe to this extreme version seemingly accept an agenda that borders on the mystical, the implication being that the Universe is a goal-oriented, comfortable abode perfectly tailored for the emergence of intelligent life. Proponents apparently want to believe that humanity is exceptional, even perhaps unique, as though the Universe has toiled specifically and necessarily to yield us. However, strongly anthropic reasoning is demonstrably tautological, even teleological—humankind's latest attempt to reinstate for itself a special position in the cosmos, to argue for a purposeful design, and thence a Designer, in Nature.

Multiple universes are often postulated by those troubled by the strong anthropic principle, and who wish to avoid its above-stated dilemma without resorting to unacceptably large coincidences. A whole family of universes, all simultaneously present yet each with a different set of physical constants, would permit one such Universe—namely, the one we inhabit—to have the "right" set of constants for the onset and endurance of stars, life, and all the other complex structures around us. However, the concept of multiple universes is unviable, implying a huge semantics problem. It represents an attractive idea in science fiction, yet