# 2 Non-equilibrium Thermodynamics in an Energy-Rich Universe

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**Summary.** Free energy, the ability to do work, is the most universal currency known in the natural sciences. In an expanding, non-equilibrated Universe, it is free energy that drives order from disorder, from big bang to humankind, in good accord with the second law of thermodynamics and leading to the production of entropy. On all scales, from galaxies and stars to planets and life, the rise of complexity over the course of natural history can be uniformly quantified by analyzing the normalized flow of energy through open, non-equilibrium, thermodynamic systems.

## 2.1 Introduction

Emerging now from modern science is a unified scenario of the cosmos, including ourselves as sentient beings, based on the time-honored concept of change. Change does seem to be universal and ubiquitous, much as the ancient Greek Heraclitus claimed long ago: "Nothing permanent except change ... all flows." Twenty-five centuries later, evidence for change abounds, some of it obvious, other subtle. From galaxies to snowflakes, from stars and planets to life itself, we are weaving an intricate pattern penetrating the fabric of all the natural sciences—a sweepingly inclusive view of the order and structure of every known class of object in our richly endowed Universe.

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 all space and across all time. These are the physical, biological, and cultural changes that have produce, in turn, our Galaxy, our Sun, our Earth, and ourselves. The result is a grand evolutionary synthesis bridging a wide variety of scientific specialties—physics, astronomy, geology, chemistry, biology, and anthropology, among others—a genuine narrative of epic proportions extending from the beginning of time to the present, from big bang to humankind.

Yet questions remain: How valid are the apparent continuities among Nature's historical epochs and how realistic is this quest for unification? Can we reconcile the observed constructiveness of cosmic evolution with the inherent destructiveness of thermodynamics? Is there an underlying principle, a unifying law, or perhaps an ongoing process that does create, order, and

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maintain all structures in the Universe, enabling us to study everything on uniform, common ground – "on the same page," sort to speak.

Recent research, guided by notions of unity and symmetry and bolstered by vast new databases, suggests affirmative answers to some of these queries: Islands of ordered complexity – namely, open systems such as galaxies, stars, planets, and life forms that produce entropy to maintain order – are more than balanced by great seas of increasing disorder elsewhere in the environments beyond those systems. All can be shown to be in quantitative agreement with the principles of thermodynamics, especially non-equilibrium thermodynamics. Furthermore, flows of energy engendered largely by the expanding cosmos do seem to be as universal a process in the origin of structured systems as anything yet found in Nature. The optimization of such energy flows might well act as the motor of evolution broadly conceived, thereby affecting all of physical, biological, and cultural evolution (Chaisson 2001).

## 2.2 Time's Arrow

Figure 2.1 shows an archetypal sketch of cosmic evolution – the "arrow of time." 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 in the early Universe to order more recently. That sequence, as determined by a large body of post-Renaissance data, accords well with the idea that a thread of change links the evolution of primal energy into elementary particles, the evolution of those particles into atoms, in turn of those atoms into galaxies and stars, and of stars into heavy elements, further in turn the evolution of those elements into the molecular building blocks of life, of those molecules into life itself, and of intelligent life into the cultured and technological society that we now share. Despite the compartmentalization of today's academic sciences, evolution knows no disciplinary boundaries.

As such, the most familiar kind of evolution – biological evolution, or neo-Darwinism – is just one, albeit important, subset of a much broader evolutionary scheme encompassing more than mere life on Earth. 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 notion that humans basically 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 stars and galaxies beyond.

Time's arrow implies no anthropocentrism. It merely provides an intellectual roadmap that symbolically traces increasingly complex structures, from spiral galaxies to rocky planets to reproductive beings. Nor does the arrow mean to imply that "lower," primitive life forms biologically changed directly