

We may see ourselves as distinct from the rest of the universe, and arbitrary boundaries of scientific disciplines may reinforce this, but an emerging theory of cosmic evolution challenges us to recognise how interconnected the universe really is, and how the processes that shape galaxies and stars also pave the way for human beings and their culture. **Eric Chaisson** outlines his unique “theory of everything”

The great unifier

■ AS WITH so many things, the Greeks had it about right. The most famous aphorism of Heraclitus, a philosopher who pre-dated Socrates, was: “*Panta rhei kai ouden menei*” or “everything flows, nothing stands still”. As scientists, we have lots of evidence for the idea that change is permanent everywhere. And now from galaxies to snowflakes, from stars and planets to life itself, the idea of ubiquitous change, or evolution, is helping us weave the natural sciences into a common fabric, stamped with an intricate pattern reflecting the order and structure of every type of object in our richly endowed universe. The result is a grand evolutionary synthesis bridging a wide variety of specialties – including physics, astronomy, geology, chemistry, biology and anthropology – a genuine narrative of epic proportions extending from the big bang to humankind.

Today’s researchers are embracing interdisciplinarity: we think bigger by working out how all known objects – from atoms to galaxies, from cells to brains, from people to society – are interrelated. The closer we look, the more everything seems related to everything else. Our appreciation of evolution now extends so far beyond biology that the general concept has become a powerful unifying factor in science.

The underlying question evolution poses is how does complexity arise in the universe? So our evolutionary quest is taking us inexorably towards complexity – a term denoting a state of intricacy, complication, variety or involvement, as in the interconnected parts of a system. Particularly intriguing is the fact that complexity seems to have increased over time, and dramatically so in the past half-billion years since the start of the Cambrian era.

We have a lot to understand about complexity, but one thing about it is certain: islands of ordered complexity – for example, open systems such as galaxies, stars, planets and life forms – are more than balanced by the great seas of increasing disorder surrounding them. This fits with the principles of thermodynamics, especially non-equilibrium thermodynamics. And there’s more: energy flows caused

largely by the expanding cosmos seem to be as common in the origin of structured systems as anything found in nature. The optimisation of such energy flows might even act as the motor of evolution – in its broadest sense.

But to make more progress with our quest to understand how evolution might work as a unifying principle across science, we face some interesting challenges. Probably the biggest is how to quantify complexity. Despite my optimism about interdisciplinary research, and the fact that researchers from many disciplines are busy grappling with complexity, their views are often restricted to their own specialties and their focus is non-unifying. Few agree on how to use the term: for example, some aspire to model biological complexity in terms of genome size (without the junk), while others prefer the morphology and flexibility of behaviour and still others look to the number of cell types, or even physical sizes of organisms.

To me, however, energy, especially energy flow, seems to be a more useful way to quantify it, no matter what system is at hand. It’s easy to model physical or biological systems by their energy budgets. And we can use energy budgets to model cultural systems: machines, cities, economies are all described, at least in part, by energy flow.

Yet it’s not just energy, it can’t be, for the most primitive weed in my backyard is surely more complex than the most intricate nebula in the Milky Way. Stars have much more energy than any life form, and the larger galaxies still more, so our measure of complexity cannot be energy alone, nor energy flow.

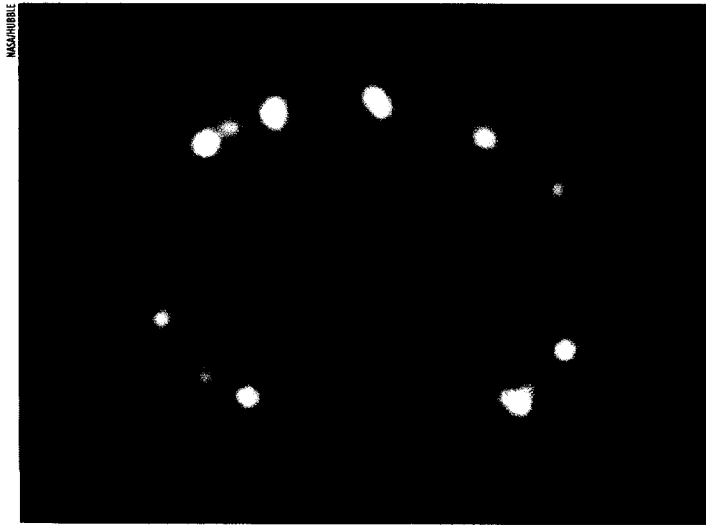
But if we look at energy flow in relation to mass, we find a real and impressive trend of increasing energy per time per mass for all ordered systems over more than 10 billion years of the universe’s existence. This “energy rate density” is a useful way to characterise or quantify the complexity of any system be it physical, biological or cultural: it is a potential common currency between them. Energy, the ability to do work, is the big commonality in the natural sciences. And in an expanding, non-equilibrated universe, it is “free” energy that drives order to emerge from chaos.

Consider stars and their progressive changes. Stars grow in complexity as their thermal and elemental gradients steepen: more information is needed to describe them as they age. “Ordered” energy flows increase from protostars at “birth”, to main-sequence stars at ▶

From galaxies to living systems, evolution may be at work in its broadest sense

Profile

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Paradoxically, the destructive force of a supernova (above) represents the most “evolved” state that any star could aspire to

maturity, to red giants near “death”. On and on the cycle churns: build up, break down, change as a kind of stellar “evolution” minus any genes, inheritance or overt function.

Consider life itself, which may well be dictated by energy flows. With few exceptions, energy-flow diagnostics show rising complexity throughout biological evolution. Life forms process more energy per unit mass than any star, and increasingly as they evolve. Starting with life’s precursor molecules all the way up to plants, animals and brains, the greater the complexity of a system, the greater the flow of energy density through that system, either to build it or maintain it, or both.

Consider society. We can trace social progress in terms of energy consumption through a variety of advances among our hominin ancestors. The energy rate density increases from the hunter-gatherers of 100,000 years ago through agriculturists of several thousand years ago to industrialists of recent history. Here, along the path to civilisation, as well as among the bricks, chips and machines of our gadget-rich society, energy is a principal driver.

Energy flow is aided and abetted by a process found among all ordered systems that looks to be first cousin to Darwin’s selection. Some kinds of selection are seen during physical evolution in simpler systems and during cultural evolution in some of the most complex systems as well as, of course, during biological evolution. Not that genes are involved in physical or cultural change, nor that inheritance and reproduction are prominent in any but the biological type of evolution, or that “natural”, or Darwinian, selection works among inanimate objects. Yet the general process of selection affects all of cosmic evolution, operating in realms well beyond biology.

Actually, the term selection is a bit of a misnomer: there is no known agent that “selects”. Selection is not an active force or promoter of evolution as much as a passive pruner of the unfit. As such, selected objects are simply those remaining after the poorly adapted ones have been removed. A better term might be “non-random elimination”, since what is really meant is the aggregate of adverse circumstances responsible for the deletion of some members of a group.

Selection works alongside the flow of energy into and out of all open systems, including life forms, often providing an important step in the production of order. Ordered systems are “selected” partly by

their ability to command energy resources: not so much energy as to be destructive and not so little as to be ineffective. Sometimes, when the energy flow exceeds a critical threshold, thereby driving a system well beyond equilibrium, selection helps the emergence of newly ordered forms – a process underlying self-assembly.

Nature displays many examples of selection among inanimate systems, but the selection is always simpler than that among living things, and always, it seems, in the presence of energy. For example, pre-biological molecules bathed in energy were “selected” in a soupy sea to become the building blocks of life. Some kinds of bonding of amino acids were selected while other kinds were excluded, implying that the “chemical evolutionary” steps toward life yielded new states more thermodynamically stable than their precursor molecules, just as long as entropy increased in their watery surroundings. Selection – or rather, chemical selection – was clearly working to help tame chance, albeit not the more subtle yet powerful Darwinian, biological selection of species modification, inheritance and adaptation.

Even at the level of crystal growth we can find a kind of selection – this time physical selection – helping to order non-living substances in much simpler ways than in biological selection. To grow an ice crystal, water molecules must collide so that they stick and are not rejected. Although the initial molecular collisions are entirely random, the migrating molecules are guided by well-known electromagnetic forces into favourable positions on the surface. If the incoming molecule lands at a surface position that’s good for the growth of ice crystal structure, then it’s “selected” to stay and contribute to the crystal, otherwise it is expelled. Its arrival is random, but the result is not.

Stars are another good example of this kind of selection. Take the sun. In about 5 billion years it will enter its red-giant phase, increasing its thermal and chemical gradients from core to surface. However, the sun will never fuse carbon into heavier elements and never detonate as a supernova. In short, the sun will not be selected to evolve any further since its energy flow will fail to reach the critical values needed for the natural emergence of greater complexity. Although our sun is not alive by any stretch of the imagination, among its stellar companions it will have been non-randomly eliminated from further stellar evolution.

“We should be able to prove that there is a cosmic evolution that binds the universe together”

Likewise, selection – call it cultural selection – was just as surely at work more recently among our ancestors. The ability to start a fire, for example, would have been a major selective asset for those hominins that possessed it, as are, in today’s world, economic competition and customer demand when combining to create selection pressure for better products in the social marketplace.

Selection operates in inanimate, non-biological systems, even if not as robustly as for living systems. Physical and chemical selection obeys well understood, if statistical, laws of physics, while biological selection is richer and more multifaceted, drawing on genetic exchange and vast information storage. Even so, these mechanisms, including accelerated cultural selection throughout our technological society, help build order and complexity in basically the same way: they mix a random initiator with a deterministic response in the presence of energy, a theme that looks integral to the onset of structure throughout nature.

So, provided we keep thinking and researching broadly enough, we should be able to prove that there is indeed a deep unity in the universe – a cosmic evolution that binds the universe together. ●