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Evolution and Emergence: An Introductory Perspective

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This article offers an overview of cosmological evolution that aims to set in context some further articles in this issue's Focus. It was originally delivered as the introduction to a session on 'evolution and emergence' held at the Liverpool Academia Europaea General Meeting of September 2008.

This isn't a sermon but I'll start with a text – the famous closing lines of the 'Origin of Species':

> There is a grandeur in this view of life … Whilst this planet has gone cycling on according to the fixed law of gravity, from so simple a beginning, forms most beautiful and most wonderful have been and are being evolved.

Darwin's 'simple' beginning – the newly formed Earth – is already very complex, chemically and geologically. Astronomers aim to trace things back far further – to set Darwin's vision in a still broader expanse of space and time. We are starting to understand how, beginning from some still mysterious genesis event nearly 14 billion years ago, atoms, stars, planets, and biospheres evolved – and how, on at least one planet around at least one star, Darwinian selection led to the emergence of creatures able to ponder their origins. That's a key theme of the present Focus. In this introductory article I shall offer a brief cosmic context.

One important realisation during the last decade is that many (perhaps most) stars have retinues of planets. So far, we can only detect big ones – like Jupiter and Saturn, the giants of our Solar System. But an astronomical highlight of 2009 was the launch in March of NASA's Kepler spacecraft, which should be sensitive enough to reveal planets no bigger than our Earth by detecting the slight dimming of a star when a planet transits in front of it. It will be a decade or two before we can actually image Earth-like planets – a firefly next to a searchlight – using giant arrays in space or the next generation of ground-based optical telescopes.

Life's origin on Earth is still a mystery, so we cannot lay firm odds on its likelihood elsewhere. But we may learn, in the coming decades, whether biological evolution is unique to the 'pale blue dot' in the cosmos that is our home, or whether Darwin's writ runs in the wider universe. The quest for alien life is perhaps the most fascinating challenge for 21st century science – its outcome will influence our concept of our place in nature as profoundly as Darwinism has over the last 150 years.

As well as stars themselves, we see places where stars are still forming – condensing from a dusty, slowly spinning cloud, as our Solar System once did. And we see stars dying, and throwing debris back into interstellar space.

Our galaxy is a kind of ecosystem where gas is processed and recycled through successive generations of stars. This process generates, from pristine hydrogen, the elements of the periodic table. All the carbon, oxygen and iron on Earth, and in our bodies, are ashes from long-dead stars. We are the 'nuclear waste' from the fusion power that makes stars shine. We can understand why carbon and oxygen are common; why gold and uranium are rare.

Let us now enlarge our horizons further. If we could get two million lightyears away and look back, our home Galaxy – the vast band of stars that we call the Milky Way – would look something like the Andromeda galaxy does to us. A vast disc, viewed obliquely, containing a hundred billion stars orbiting a central hub. Our Sun would be an ordinary star, out towards the edge. Within range of powerful telescopes are many billions of galaxies.

We can now look very far back in time. Deep exposures with the Hubble Space Telescope show that the sky is densely speckled with faint smudges of light. Each smudge is actually an entire galaxy, which appears so small and faint because of its huge distance. The light from these remote galaxies set out as much as 10 billion years ago. These galaxies are being viewed when they have only recently formed. Some consist mainly of glowing diffuse gas that hasn't yet condensed into stars.

What happened before galaxies formed? Cosmologists are confident that this whole panorama – as far as our telescopes can see – is the expanding aftermath of a 'big bang' nearly 14 billion years ago. Cosmic history can be traced back to a hot dense state – a state that was almost homogeneous (and the word 'almost' is important). We can be very confident back to a second, and fairly confident back to a microsecond. But the initial tiny fraction of a second is still shrouded in uncertainty, because the physical conditions were then more extreme than can be simulated in our laboratories – even at the Large Hadron Collider (LHC) in Geneva.

Our present complex cosmos manifests a huge range of temperature and density – from blazingly hot stars, to the dark night sky. People sometimes worry about how this intricate complexity emerged from an amorphous fireball. It might seem to violate a hallowed physical principle – the second law of thermodynamics – which describes an inexorable tendency for patterns and structure to decay or disperse.

The answer to this seeming paradox lies in the force of gravity, which reverses our normal intuitions from thermodynamics. Self-gravitating systems – stars, for instance – have negative specific heat. If the nuclear burning in the Sun were to turn off, the Sun would slowly deflate as it lost heat – but its centre would get hotter as well as denser. Gravity drives things further from equilibrium.

And even in the early amorphous stage of cosmic expansion, before stars formed, gravity was enhancing the density contrasts. Any patch that starts off slightly denser than average would decelerate more, because it feels extra gravity; its expansion lags further and further behind, until it eventually stops expanding and separates out.

Astrophysicists have carried out extensive computer simulations of 'virtual universes'. The simulations show incipient structures unfolding and evolving into galaxy-scale concentrations of material, within which gravity enhances the contrasts still further, and gas is compressed into stars. Each galaxy is an arena within which stars, planets and perhaps life can emerge.

Where did the initial fluctuations come from? The answer takes us into speculation about the very earliest stages – when the universe was far less than a microsecond old, and energies and densities were so extreme that experiments offer no direct guide to the relevant physics.

The magazine *Discover* once had a cover picture that showed a red circle, beneath the caption 'the universe when it was a trillionth of a trillionth of a trillionth of a second old – actual size'. According to a popular theory, the entire volume we can see with our telescopes 'inflated' from a hyper-dense blob no bigger than that; the irregularities that form galaxies and larger structures started out as microscopic quantum fluctuations generated at that time; and it was at that time that the content of the universe – the mix of nucleons, dark matter and radiation – was established.

There is an interconnectedness between microworld and cosmos – between the inner space of atoms and the outer space of the universe. There are links between small and large. Our everyday world – of life and mountains – is determined by atoms and chemistry. Stars are powered by the fusion of nuclei within those atoms. Another link is that galaxies are seemingly held together by swarms of subnuclear particles that make up the 'dark matter'.

The microworld is the domain of the quantum. On cosmic scales, Einstein's theory holds sway. General relativity and quantum theory are the twin pillars of 20th century physics. But they haven't yet been meshed together into a single unified theory. In most contexts, this does not impede us because their domains of relevance do not overlap. Astronomers can ignore quantum fuzziness when calculating the motions of planets and stars. Conversely, chemists can safely ignore gravitational forces between individual atoms in a molecule because they are nearly 40 powers of ten feebler than electrical forces. But at the very beginning, everything was squeezed so small that quantum fluctuations could shake the entire universe.

To confront the overwhelming mystery of what banged and why it banged we need a unified theory of cosmos and microworld. A unified theory is the key unfinished business for science today. The most favoured theory posits that the particles that make up atoms are all made up of tiny loops, or strings, that vibrate in a space with 10 or 11 dimensions. This string theory involves intensely complex mathematics that certainly cannot be found on the shelf, and the challenges it poses have been a stimulus for mathematics. Ed Witten, the acknowledged intellectual leader of string theory, ranks as a world-class mathematician, and several other leading mathematicians have been attracted by the challenge.

String theory is not the only approach to a unified theory, but it is by far the most intensively studied one. This endeavour is surely good for mathematics, but there is controversy about how good it is for physics. Arguments rage over whether string theory is right, whether it will ever engage with experiment, and even whether it is physics at all. There have even been commercially successful books rubbishing the idea.

To me, criticisms of string theory as an intellectual enterprise seem in poor taste. It is presumptuous to second-guess the judgement of people of acknowledged brilliance who choose to devote their research career to it. Finding a unified theory of all the fundamental forces would be the completion of a programme that started with Newton (who showed that the force that holds planets in their orbits is the same that makes an apple fall) and continued through Maxwell, Einstein and their successors. String theory, if correct, would also vindicate the vision of Einstein and the late American physicist John Wheeler that the world is essentially a geometrical structure.

An interesting possibility, which I think should not be dismissed, is that a ‘true’ fundamental theory exists, but that it may just be too hard for human brains to grasp. A fish may be barely aware of the medium in which it lives and swims; certainly it has no intellectual powers to comprehend that water consists of interlinked atoms of hydrogen and oxygen. The microstructure of empty space could, likewise, be far too complex for unaided human brains to grasp.

String theories involve scales a billion billion times smaller than any we can directly probe. At the other extreme, our cosmological theories suggest that the universe is vastly more extensive than the patch we can observe with our telescopes. It may even be infinite. The domain that astronomers call ‘the universe’ – the space, extending more than 10 billion light years around us and containing billions of galaxies, each with billions of stars, billions of planets (and maybe billions of biospheres) – could be an infinitesimal part of the totality.

Now for another question: how big is the universe? We can only see a finite volume – a finite number of galaxies. That is essentially because there's a horizon – a shell around us, delineating the distance light can have travelled since the big bang. But that shell has no more physical significance than the circle that delineates your horizon if you're in the middle of the ocean. We'd expect far more galaxies beyond the horizon.

There's no perceptible gradient across the volume of space-time within range of our telescopes – that fact alone suggests that the domain astronomers can see could be only a tiny fraction of the aftermath of our big bang. It may go on much further – even for ever. But that is not all. 'Our' big bang may not be the only one. What we have traditionally called 'the universe' could be just one patch of space-time in a vast cosmic archipelago. This hugely expanded cosmic perspective takes Copernican modesty one stage further. To put this on a firm footing, we'll need a unified theory that links the very large and the very small.

There is, however, a third frontier on intermediate scales: very complex entities such as us. We ourselves are midway between atoms and stars: large enough, compared to atoms, to have layer upon layer of intricate structure; but not so large that we're crushed by our planet's gravity. To understand ourselves, we must understand the atoms we're made of, and the stars that made those atoms.

But stars are simple: they're so big and hot that their content is broken down into simple atoms – stars don't match the intricate structure of even an insect, let alone the human brain. (I really mean this – I'm not just being polite to the biologists.)

We can identify the key stages in the emergence of complexity. The first particles – protons and neutrons. The first stars and galaxies. The synthesis of the periodic table in stars. Formation of planets around later-generation stars. And then of course, on at least one planet, the formation of a biosphere, that leads to the emergence of brains capable of pondering their origins.

What are the key prerequisites for a universe that can offer the arena for this chain of events? Crucial to the whole emergent process is gravity – which enhances density contrasts, and allows structures to form. It is a very weak force. But, unlike the electrical force, everything has the same 'sign' of gravitational charge: when sufficiently many atoms are packed together, gravity wins. It is unimportant for an asteroid-size lump. But it makes planets round, and any object more massive than Jupiter is squeezed to make a star. The fact that, for individual protons, it is weaker by 36 powers of 10 than the electrical force, means that there can be many layers of structure between the microworld and the scales that get crushed by gravity.

In addition, stars are not only big but live a long time. And any emergent complexity – like the growth of an animal, requires billions of successive chemical reactions, and Darwinian evolution requires millions of generations of animals. So, although gravity is crucial, ironically, the weaker it is, the better. Were it stronger, stars (gravitationally confined fusion reactors) would be much smaller and wouldn't last long. Creatures like us would be crushed by gravity. The strength of gravity, compared with other forces, is one of the key numbers of physics not yet explained.

Another requirement for a biosphere is that chemistry should be non-trivial. This requires a balance between the nuclear force (the 'strong' interactions that bind together the protons in a nucleus) and the electric repulsive force that drives them apart. Otherwise there would be no periodic table.

There are other requirements. The universe must contain an excess of matter over antimatter. It must expand at the 'right' rate – not collapse so soon that it offers inadequate time for the emergence of complexity, or expand so fast that gravity cannot pull together the structures that lead to stars and galaxies. And there must be some fluctuations for gravity to feed on. Otherwise the universe would now be cold ultra-diffuse hydrogen – no stars, no heavy elements, no planets and no people.

To understand these numbers is a challenge to fundamental physics and cosmology. And there is a key question: are the numbers the same over the entire domain we observe? It remains a possibility that, far beyond our horizon, they take different values. Whether this is so is a topic of key debate. Perhaps the numbers are genuinely universal. But perhaps in the grandest perspective, what we call the laws of nature are mere parochial bylaws. Four-hundred years ago, Kepler thought that the Earth was unique, and its orbit was a circle, related to the other planets by beautiful mathematical ratios. We now realise that there are billions of stars, each with planetary systems. Earth's orbit is special only insofar as it's in the range of radii and eccentricities compatible with life.

Maybe we're due for an analogous conceptual shift, on a far grander scale. Our big bang may not be unique, any more than planetary systems are. Its parameters may be 'environmental accidents', like the details of the Earth's orbit. In this hugely expanded cosmic perspective, what we've traditionally called fundamental constants and laws could be mere parochial bylaws in our cosmic patch. They might derive from some overarching theory governing the ensemble, but not be uniquely fixed by that theory. The hope for neat explanations in cosmology may be as vain as Kepler's numerological quest. Our universe isn't the neatest and simplest. It has a rather arbitrary-seeming mix of ingredients – in the parameter range that allows us to exist.

We don't know if these conjectures are right. They're speculative science, not metaphysics. What could give us confidence in unobservable domains? The answer seems clear – we will believe in them if they are predicted by a theory that gains credibility because it accounts for things we can observe. We believe in quarks, and in what general relativity says about the inside of black holes, because our inferences are based on theories corroborated in other ways.

A challenge for 21st century physics is to decide whether there have been many ‘big bangs’ rather than just one – and (if there are many) how much variety they might display.

These still unsettled debates are very important. Nonetheless, for 99% of scientists, they are irrelevant. The task of chemists, geophysicists and biologists is to understand the complexity that’s the eventual outcome of cosmic processes.

The sciences are sometimes likened to different levels of a tall building – particle physics on the ground floor, then the rest of physics, then chemistry, and so forth: all the way up to psychology – and the economists in the penthouse. There is a corresponding hierarchy of complexity: atoms, molecules, cells, organisms, and so forth. But the analogy with a building is poor. The ‘higher level’ sciences dealing with complex systems are not imperilled by an insecure base, as a building is. They have their own autonomous concepts and theories.

To understand why flows go turbulent, or why waves break, subatomic details are irrelevant. We treat the fluid as a continuum (and even if we could solve Schrödinger’s equation for every atom of a turbulent fluid, it wouldn’t offer any insight into turbulence).

An albatross returns predictably to its nest after wandering ten thousand miles in the southern oceans. But this is not the same kind of prediction as astronomers make of celestial orbits. And scientific statements about humans are more different still.

Problems in biology, and in environmental and human sciences, remain unsolved because scientists don’t understand subatomic physics well enough. Stars are simple: they’re so big and hot that their content is broken down into simple atoms – none match the intricate structure of even an insect.

One final question – is there a special perspective that astronomers can offer to evolutionary science? Astronomers can set our home planet in a vast cosmic context: billions of galaxies, each containing billions of planets. Even more, they can offer intimations that physical reality is hugely more extensive – and perhaps far more intricate – than the volume we can observe with our telescopes. Moreover, astronomers can offer an awareness of an immense future.

The stupendous timespans of the evolutionary past are now part of common culture. Our present biosphere is the outcome of more than four billion years of evolution. But most people still somehow think we humans are necessarily the culmination of the evolutionary tree. That hardly seems credible. Our Sun formed 4.5 billion years ago, but it will take 6 billion more before the fuel runs out. It then flares up, engulfing the inner planets and vaporising whatever remains on Earth. And the expanding universe will continue – perhaps for ever – destined to become ever colder, ever emptier.

Any creatures witnessing the Sun’s demise 6 billion years hence, here on earth or far beyond, won’t be human – they’ll be as different from us as we are from the first monocellular organisms. So a question for the biologists is: could we be barely at the half way stage of evolutionary development? Could post-human evolution be as prolonged as pre-human?

But let us finally focus back on the here and now. Even in this ultra-compressed timeline – extending billions of years into the future, as well as into the past – this century may be a defining moment. It is the first in our planet's history where one species – ours – has Earth's future in its hands, and could jeopardise not only itself, but life's immense potential.

So this pale blue dot in the cosmos is a special place. And we are its stewards at an especially crucial era.

About the Author

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