Complexity and Analogy in Science
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From Big Bang to Biospheres: The Scope and Limits of Explanation

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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. Gravity enhances density contrasts rather than wiping them out. Any patch of the expanding universe that started off slightly denser than average would decelerate more, because it would 'feel' extra gravity; its expansion would lag further and further behind, until it eventually stopped expanding and separated out. Cosmologists are now able to generate computer simulation of a segment of a 'virtual universe'. These simulations start off with a dense and almost-uniform universe, and depict how, as it expands, incipient structures unfold and evolve into the precursors of the first galaxies. In these galaxy-scale clumps gravity enhances the contrasts still further; gas is pulled in, and compressed into stars. Each galaxy is an arena within which stars, planets and perhaps life can emerge.

The conditions prevailing in the very earliest stages of the universe – within the first tiny fraction of a second – are uncertain. This is primarily because the densities and energies were more extreme than can be achieved on Earth, even in a machine like CERN's Large Hadron Collider. However, at the later stages, our models have a firmer foothold in experiment (corroborated now by astronomical observations), and we can identify some key stages:

(i) Protons and neutrons combine in the first three minutes to make deuterium and helium.

(ii) Everything expands, cools and dilutes until the gas becomes neutral and transparent. And the universe enters a literal dark age when the cooling shifts the primordial light into the infrared.

(iii) After about 100 million years the first stars form and light up the universe again.

(iv) The stars then assemble into galaxies. Fusion processes within the stars synthesis the periodic table from pristine hydrogen. Short-lived stars of high mass end their lives as supernovae, and fling this processed material back into space. Second-generation stars (our Sun among them) condense from interstellar clouds already contaminated by the debris from earlier supernovae. Indeed each of us contains atoms of carbon, oxygen and phosphorus that were forged in hundreds of ancient stars spread across the Milky Way.

Crucial to the whole process is gravity. This force has the perverse thermodynamic property of driving things further from equilibrium. Gravitating structures have a negative specific heat. As they lose energy, they get hotter. If the nuclear reactions that generate its power were switched off, the Sun would gradually contract, but in the process its centre would get hotter: higher pressure is needed to balance gravity as it gets smaller.

Gravity is a very weak force. On the atomic scale, it is about 40 powers of ten weaker than the electric force between an electron and a proton. Chemists do not need to worry about the gravitational forces within the molecules or crystals they study. But in any large object, positive and negative charges almost exactly cancel. In contrast, everything has the same 'sign' of gravitational charge so when sufficiently many atoms are packed together, gravity wins.

Figure 1 depicts this trend. It shows, on a logarithmic scale, the masses and radii of various objects. Black holes, with mass proportional to radius, lie along a line of slope 1. Note that a black hole the size of a nucleus has the mass of about 10^{38} protons – billions of tons. Small holes are so massive because gravity is weak. Solids – sugar lumps, rocks, and asteroids, lie on a line of slope 3. The gravitational binding energy per particle grows as the 2/3 power of mass, so solid objects get closer to the black hole line as their mass goes up. Gravity is unimportant up to asteroid-size lumps. But it makes planets round, and any object more massive than Jupiter is squeezed to make a star. We see clearly from this diagram why the characteristic number of protons in a star is the 3/2 power of the large number that reflects the weakness of gravity on the atomic scale (right on the left, is where quantum theory and gravity meet. The Planck mass – when a black hole is no bigger than its Compton wavelength).

From diagrams like this you could predict what stars were like even if you lived on a perpetually cloud-bound planet. Were gravity not so weak, this graph would have the same shape, but there would be fewer powers of ten between the micro and the cosmic scales – and less space and time for complexity.

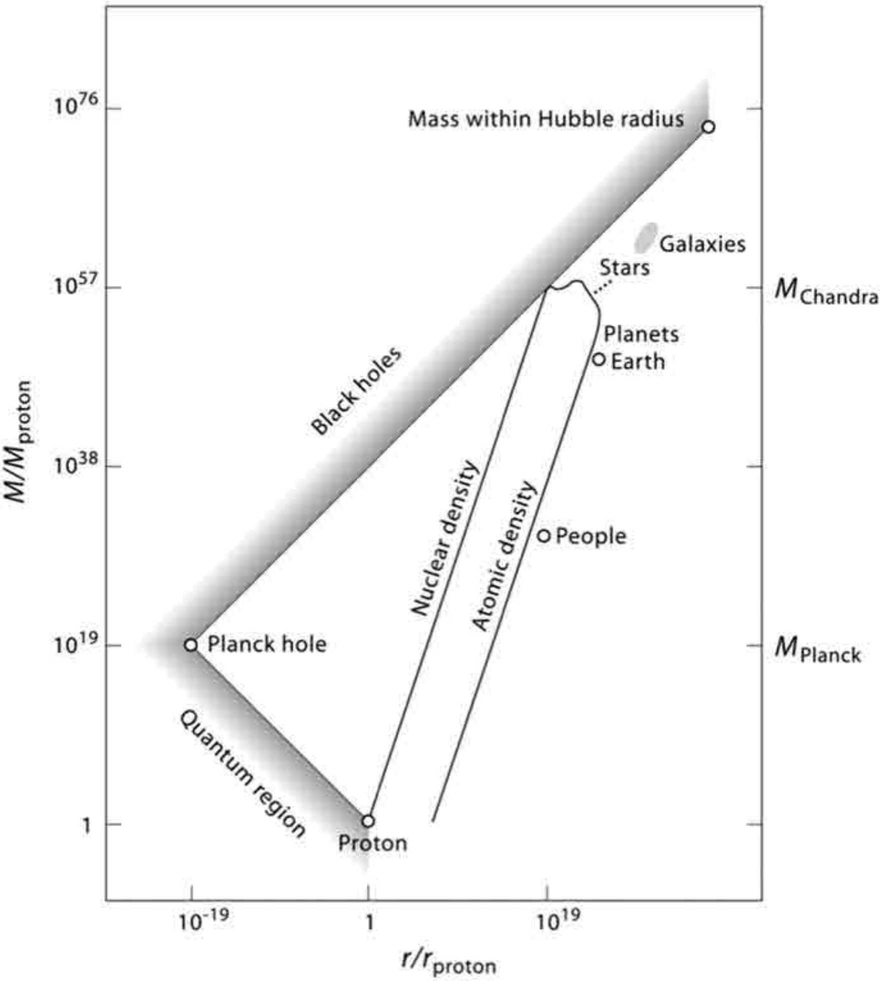

Figure 1.

Let's now step back a bit and ask what are the essential features of our universe that allow it to evolve from an amorphous dense beginning into its present complexity.

(i) As already mentioned, gravity is crucial. It has to be very weak. Indeed, up to a point, the weaker the better. We might live in a more interesting universe if gravity were (say) ten times weaker than it actually is. Stars would be bigger and would live longer. Objects could grow larger without being crushed by gravity, and evolutionary emergence could extend over an even longer timespan.

And there are other requirements:

(ii) There could be no complexity if the universe stayed in thermal equilibrium, as it was for its first half million years. The emergence of life requires temperature contrasts. We and all living things depend on 'high grade' energy from the Sun; this is processed via photosynthesis and re-emitted from the Earth as infrared radiation; it escapes into intergalactic space where the temperature is only 2.7 degrees above absolute zero.

(iii) There must be an excess of matter over antimatter in the hot early universe. Otherwise almost all particles would annihilate with antiparticles as the universe expanded and cooled, leaving just radiation. The detailed mechanism that establishes a 'favouritism' for matter over antimatter is still a matter of discussion.

(iv) Another requirement for stars, planets and biospheres is the possibility of complex chemistry. If hydrogen were the only element, chemistry would be dull. The existence of a periodic table of stable elements requires a balance between the nuclear force (the so called 'strong' interactions that bind together the protons in a nucleus) and the electric repulsive force that drives them apart. And if complex nuclei were not strongly bound together, the energy that powers the stars would not exist.

(v) There must be stars. Indeed there must be at least two generations of stars. The first synthesizes the elements of the periodic table. A second generation of protostars then contracts from slowly rotating interstellar clouds enriched in heavy elements (in dust and gaseous form). During the contraction, the protostar conserves angular momentum and spins faster, eventually spinning off a dusty disk from which planets form.

(vi) The universe must expand at the 'right' rate – neither collapsing too soon, nor expanding so fast that gravity can't pull together the structures. This requires two conditions to be fulfilled. First, the universe must be nearly 'flat' in the technical sense that the angles of triangles add up to 180 degrees. The theory called 'inflation' suggests how this might have come about. But a second requirement is that the so-called 'cosmological constant', in effect a repulsive force generated by space itself, should not be so large that it overwhelms gravity, causing the cosmic expansion to accelerate, before the first stars and galaxies have condensed out. The fact that this force is non-zero, but so small, is a mystery that will not be solved until we understand the bedrock nature of space. It is suspected that space will have a 'grainy' structure, but on the Planck scale (see Figure 1) which is a trillion trillion times smaller than an atom.

(vii) There must be some initial fluctuations for gravity to amplify – sufficient in amplitude to permit the emergence of structures. Otherwise the universe would now be cold ultra-diffuse hydrogen – no stars, no heavy elements, no planets and no people. There are theories which suggest that these fluctuations could have been generated at an ultra-early stage in the cosmic expansion by microscopic quantum fluctuations, these fluctuations being stretched by the subsequent expansion right up to the scales of galaxies, and beyond.

Firming up our understanding of these requirements (and deciding which are 'necessary' and which are contingencies) requires progress on meshing general relativity and the quantum principle into a single unified theory. This is unfinished business for the 21^{st} (or maybe even the 22^{nd}) century. In most contexts, the lack of such a theory does not impede us because the 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 mystery of what banged and how it banged requires a synthesis between our current separate theories of the very large and the very small.

The bedrock nature of space and time, and the unification of cosmos and quantum are surely among science's great 'open frontiers'. But calling this the quest for a 'theory of everything' is hubristic and misleading. It is irrelevant to 99% of scientists. Problems in biology, and in environmental and human sciences, remain unsolved because it's hard to elucidate their complexities – not because we don't understand subatomic physics well enough. Even an insect, with its layer upon later of complexity – is harder to understand than a star, where intense heat and compression by gravity precludes complex chemistry.

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 aren't imperiled by an insecure base, as a building is. Each level has its own autonomous concepts and theories. Everything, however complicated – breaking waves, migrating birds, and tropical forests – is made of atoms and obeys the equations of quantum physics. But even if Schrodinger's equation could be solved for one of these macroscopic systems, its solution wouldn't offer the enlightenment that scientists seek. Reductionism is true in a sense. But it's seldom true in a *useful* sense.

I conclude with a speculation. Einstein averred that, "The most incomprehensible thing about the universe is that it *is* comprehensible". He was right to be astonished. Our minds, which evolved to cope with the life of our remote ancestors on the African savannah, can also comprehend the counterintuitive microworld of atoms, and the vastness of the cosmos.

But some aspects of reality might elude us simply because they're beyond human brains, just as surely as Einstein's ideas would baffle a chimpanzee. Perhaps complex aggregates of atoms, whether brains or machines, can never understand everything about themselves. I'm not suggesting that the 'big problems' that we've identified won't be solved – least of all would one wish to demotivate those who are now talking them – but we should be open to the prospect that some problems (and some aspects of reality) exist that we are not aware of.

However, our intellectual limitations are less cause for dismay if we are mindful of another important inference from cosmology: the time lying ahead is at least as long as the time that has elapsed up until now. Our Sun is less than half way through its life; and our universe may continue for even longer – perhaps forever. So humans may be far from the culmination of the evolutionary process. This process could have much further to run, here on Earth and perhaps far beyond. Indeed in future the changes could be fast, because they would be determined (or at least modulated) by conscious choices of intelligent beings rather than being the outcome of Darwinian selection. In this perspective, we should be hopeful, and consoled, that post-human intellects may, in the far future, elucidate mysteries that are beyond our grasp.