

The Computational Cosmic Brain

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Abstract The cosmic web exhibits some striking similarities to that of an animal brain. Despite its tremendous size the cosmos is many orders of magnitude less efficient at computation than the brains residing in Earth's biosphere. This shows just how information-rich life truly is.

Keywords: astrobiology, cosmic web, information theory, neural network

What drives the evolution of life on Earth? Commonplace answers include natural selection, genetic drift, and mutation. Such phenomena, while undoubtedly crucial, fail to properly explain the complex hierarchy of life on Earth which runs the gamut from molecules within cells to the entire biosphere. One fairly recent and unifying idea is that life is driven by information [1,2]. The most important organ in the human body, the brain, is in essence an information processing machine. Information flows to and from electrically excitable cells known as “neurons”. Neurons transmit information to one another via nerve fibers known as “axons”. Information is conveyed to a special junction between neurons known as a “synapse” while the receiving end of a neuron is a feathery filament known as a “dendrite”. Microscopy of brain tissues has facilitated the detailed visualization of the complex network that spans the brain. One noteworthy result is that the neural network of most animal brains displays an uncanny resemblance to the large scale structure of the Universe. This leads to the questions: *If the Universe were a cosmic brain, what would be its information capacity? Furthermore, what does such knowledge tell us about life on Earth?*

The “cosmic web” is the observable Universe on the grandest of scales. On such scales, typically measured in megaparsecs (Mpc; where 1 Mpc = 10^6 pc = 3.08×10^{22} meters), galaxies and clusters of galaxies loosely resemble neurons and are connected to each other by filaments of matter and energy, analogous to axons, synapses, and dendrites in a brain (see Figure 1). The human brain has around $N_B \sim 10^{11}$ neurons [3], with a storage capacity of $I_B \sim 10^{16}$ bits [4]. In bits per neuron (bpn) this translates to

$$S_B = \frac{I_B}{N_B} \sim 10^5 \text{ bpn.} \quad (1)$$

The human brain has $\sim 10^4$ synapses per neuron [5] and therefore $\sim 10^{15}$ synapses. In our order-of-magnitude estimate, we find the number of bits per synapse to be $10^{16}/10^{15} = 10$, which agrees remarkably well with [4], who determined that the actual value is 4.7 bits per synapse.

The network of the cosmic web is such that the smallest observable structures are formed from the gravitational instability of overdense regions. The smallest structures susceptible to gravitational collapse are comparable in mass to that of the Sun [6]. Thus, in our cosmic web analogy, we choose stars to serve as nodes. The total number of nodes in the cosmic web, N_{CW} , is 10^{11} galaxies \times 10^{11} stars per galaxy = 10^{22} . Therefore the information capacity of the cosmic web is

$$I_{CW} = S_B \times 10^{22} \text{ nodes} = 10^{27} \text{ bits.} \quad (2)$$

Here, we have explicitly assumed that the fractal nature of the cosmic web is akin to that of the human brain. In doing so, we further suppose that the number of filaments per node in the cosmic web is also comparable to the number of synapses per neuron in the brain. In principle, sub-stellar objects could also be considered nodes. As an example, if equation (2) was recalculated by incorporating planets, then I_{CW} increases by three orders of magnitude [7]. Consequently, it is possible to assume that every single particle in the Universe can act as a bit [8], in which case the information capacity catapults to $\sim 10^{90}$ bits. However, extrapolating this value, by way of analogy, to the memory capacity of a human brain is

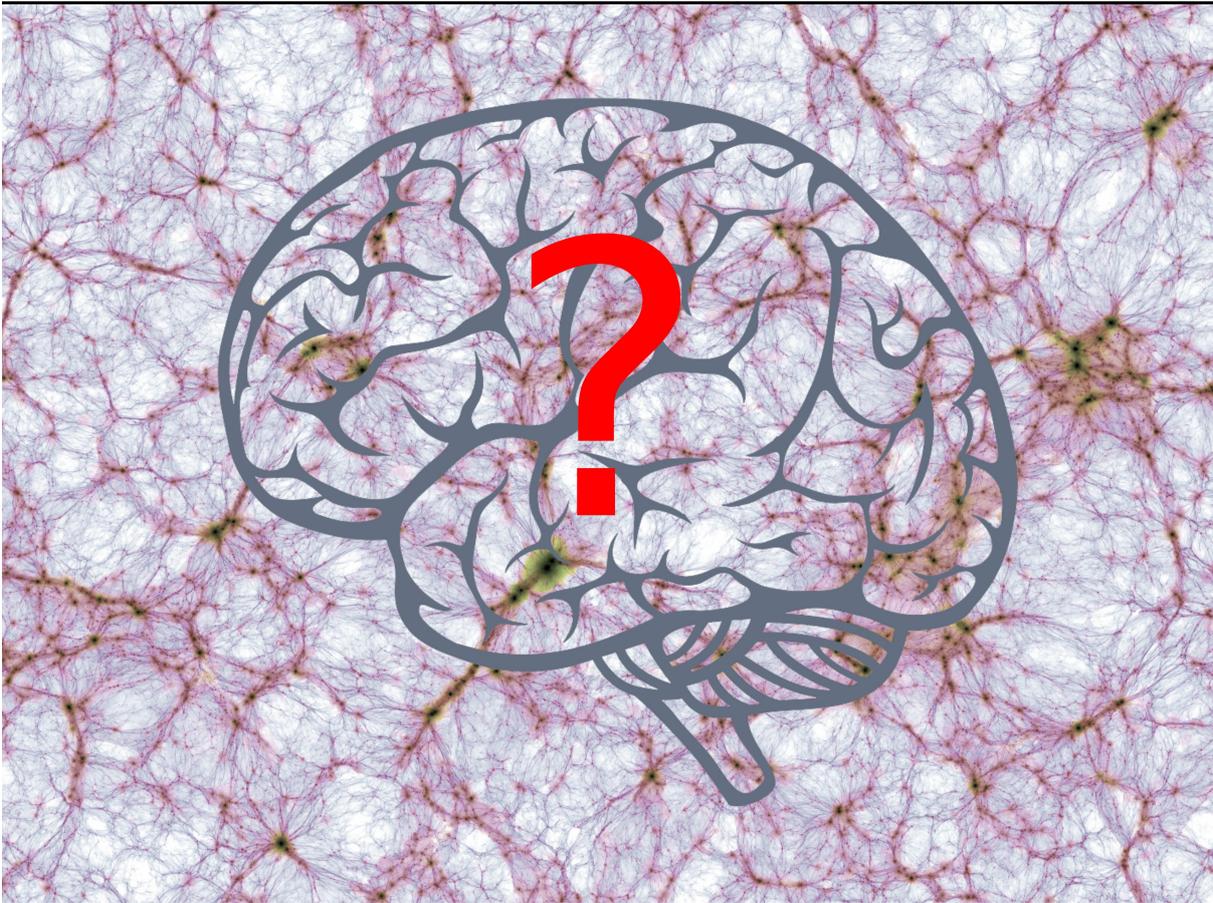


Figure 1. *The cosmic web as a giant brain?* The background in this figure depicts the baryonic density in a slice of the cosmic web that was generated during the TNG300 simulation of IllustrisTNG. The scale from left to right is nearly 370 Mpc. The observable Universe is believed to be isotropic and homogeneous, and is manifestly similar in appearance to the neural network of the brain. This parallel naturally raises questions, which this paper addresses, such as: If the cosmos were one giant brain, how does it compare with our own? (Background illustration used with permission.)

erroneous. The storage capacity of a living brain is determined by the number of neurons and synapses, not the number of atoms and other subatomic particles, whose numbers are many orders of magnitude larger.

We can see that the cosmic web, in essence the cosmos, has the computational capacity of 10^{11} modern humans. There are approximately 10^{10} people on Earth, thus it would take 10 human-filled Earths to have the same computational power as the cosmos. However, if we assume that equation (1) applies to most creatures with brains, then as a whole insects have far more computational power than the entire class *Mammalia*. The adult fruit fly, *Drosophila melanogaster*, has on the order of 10^5 neurons [9]. There are approximately 10^{19} living insects on the Earth at any given moment [10], thus the total information capacity for the class *Insecta* is 10^{19} insects $\times 10^5$ neurons $\times 10^5$ bpn = 10^{29} bits. Consequently, viewed in their entirety, insects have by far the most computational potential of all life (endowed with neural systems) on Earth. It takes only one Earth-like planet, replete with merely 1% the total population of insects relative to the Earth, to equal the computational power of the observable Universe. Another consideration is the computational surface density, which we define as

$$\Phi = \frac{I}{4\pi r^2} \quad (3)$$

where I is the information capacity and r the radius. Earth has a radius of roughly 6400 km, whereas the radius of the observable Universe is ~ 14000 Mpc [11]. Choosing $I_{Earth} \sim 10^{29}$ bits, the computational density of Earth's biosphere is $\sim 10^{14}$ bits per square meter. From (2) and (3), the cosmic information density is on the order of 10^{-28} bits per square meter. This corresponds to an amazing 42 orders of magnitude difference between our biosphere and that of the cosmic web, thus illustrating how information-rich life on Earth truly is.

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