From RNA Replicators to Genes to Survival Machines with Brains

Gyan Bhanot[1,2](✉)

[1] Department of Physics, Department of Molecular Biology and Biochemistry,
Rutgers, The State University of New Jersey, Piscataway, NJ, USA
`gbhanot@rci.rutgers.edu`
[2] Institute for Advanced Simulation (IAS) and Jülich Supercomputing Centre
(JSC), Jülich, Germany

Abstract. I describe the evolution of life and the evolution of complex dynamical systems such as the brain as an emergent phenomenon, which allow a subset of multicellular life to learn its environment and adapt to it, enabling it to survive and replicate. Its ultimate purpose is to allow organisms to project their genetic materials into subsequent generations. It can only be understood in the context of its function.

> *"If superior creatures from*
> *space ever visit earth, the first question*
> *they will ask, in order to assess the level*
> *of our civilization is*
> *'Have they discovered evolution yet?'"*
> Richard Dawkins in *"The Selfish Gene"*

1 The Origins of the Earth and the Appearance of Life

The solar system was formed approximately 5 billion years ago from the gravitational collapse of a dust cloud due to perturbations. This collapse created a proto-star, with an accretion disk around it. The proto-star evolved into the sun and the accretion disk into the planets. Using radiometric dating of terrestrial and lunar rocks and meteorites, the age of the earth is estimated to be 4.54 ± 0.05 billion years [1]. There is evidence that life began on earth around 3.6–4 billion years ago [2, 3], after the formation of a sufficiently thick crust on its molten core. The most convincing scientific theory about life's origins is its emergence from a soup of inorganic molecules under the action of heat and light in the early earth. These theories have as their underpinnings the experiments in the 1950's by Miller and Urey [4, 5], who showed that organic molecules could be synthesized out of inorganic molecules. In this experiment, they showed that when water, methane and ammonia, which were abundant on earth before

---

Invited talk given at the "International Workshop on Brain Inspired Computing: Computational models, algorithms, applications, and implementations", Cetraro, Italy, July 8–11, 2013.

L. Grandinetti et al. (Eds.): BrainComp 2013, LNCS 8603, pp. 15–21, 2014.
DOI: 10.1007/978-3-319-12084-3_2

the appearance of oxygen, were subjected to electrical discharges (lightening), they could form hydrocarbons, sugars and 11 out of the 20 amino acids which form the proteins that are the basis of all life on earth.

Early life: the RNA world: Amino acids can form long chains (RNA) with the ability to store genetic information and catalyze enzymes. The universality of the genetic code and the ubiquitous RNA/Protein Ribosome machinery that is used by all life to translate the DNA message into proteins, suggests that an RNA world preceded cellular life. Several other ribosome enzymes (ribozymes) such as the Hammerhead ribozyme, which can self-cleave [6], and RNA polymerase, with the ability to auto-catalyze [7], suggests that the RNA World is embedded in fossilized form in life today.

What was the RNA world like [8]? RNA is composed of sequences of nucleotides, which are formed from amino acids with their nitrogenous base attached to a sugar-phosphate backbone. The RNA world was likely a primordial soup of strands of RNA “living” in a sea of free-floating nucleotides. The bond between most nucleotides break easily, but some nucleotide sequences have lower energies, which may have allowed them to remain attached for a longer time. This may have created long chains of specific nucleotides that remained attached long enough to attain auto-catalysis, allowing them to self-synthesize their own sequence by harvesting the appropriate nucleotides from their surroundings. The RNA world consisted of many varieties of

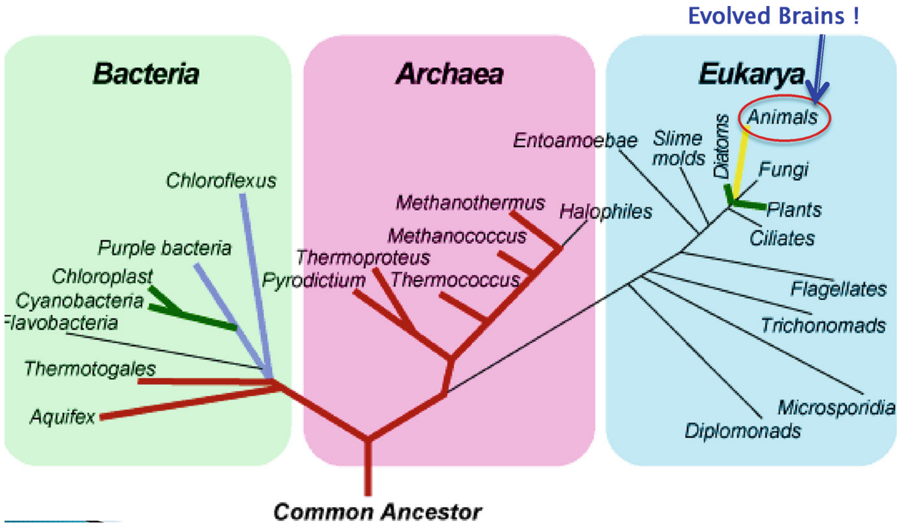

Fig. 1. The tree of life. The tree consists of three major branches, bacteria, archaea and eukarya, all evolved from a common ancestor, which was most likely evolved from an Eventually, stable varieties of replicator molecules appeared, which continued to compete for survival. Some may have built enclosures (cell walls) to protect themselves. Inside these walls, replicators became complex, and evolved methods to store (DNA), retrieve (Polymerase, Ribosomes) and process (signaling pathways) information. They invented ways of increasing stability and eliminating rivals. Eventually, they built “survival machines” (Fig. 1) which are the organisms we see in the world today (image from: http://www.astrobio.net/topic/origins/origin-and-evolution-of-life/worlds-smallest-power-station/).

"replicator" molecules, which competed electro-chemically and mechanically with each other for resources. The fitness of such replicators depended on their longevity, fecundity and accuracy of replication. The most successful ones survived, consumed or subverted the rest through their ability to outcompete the rest [8].

Brains are simulating machines: The leaves the tree of life represent extant life forms, most of which did not bother to evolve brains. Most of cellular life that exists today is single celled (unicellular). In a minority, cooperative systems of specialized cells emerged, which could outcompete their rivals. In these systems, complex, multicellular life forms arose, which abandoned the clonal immortality of unicellular life to become mortal, lumbering survival machines (SMs). They invented methods to regulate energy within cells [9], and invented suicide, death and sex [10], mechanisms, which made them fitter in projecting their RNA, DNA, genes and genomes from one generation to the next. This small minority of "animal" life, which includes humans, eventually evolved brains.

Brains are "simulating machines", which process, reduce and translate sensory cues and send appropriate instructions to sets of cells (organs) to make them perform specific actions. The goal of this processing is to increase the likelihood that the organism will not be eaten, will get sufficient nutrition to mature into an adult, find a mate and reproduce. Survival Machines who learn by "Trial and Error" get hurt. So SMs evolved brains, allowing them to distinguish friend from foe, react quickly to danger signals, retain memory of past events and seek food and mates. The reason why we have brains is that SMs with "Brains" are fitter. SMs who process sensory data and "simulate" the world better can anticipate danger, eat better, live longer, and leave more progeny.

How did neurons evolve? Neurons may have evolved in cooperative cell systems to allow specialized groups of cells to process input signals from other cells and transmit instructions to affect the behavior of distant cells in the collection. A selectively permeable membrane separates the cell interior from the exterior. Almost all eukaryotic cells maintain a small trans-membrane electric potential of between 40 and 80 millivolts between the interior (the cathode or - terminal) and the exterior (the anode or + terminal). When the cell membrane is disturbed, it gets locally depolarized, and this depolarization can spread to affect other regions of the cell and the surrounding medium. A passive or active exchange of ions across the membrane can also change the potential, and these signals can also travel into the extracellular medium and change the potential on other cells. In specialized groups of cells (neurons), the shape and relative arrangement of cells, and specific chemically or voltage gated ion-channels, permit the depolarization to propagate in a directed way, much like the signals in an electrical transmission system. In these cells, the depolarization can be sudden (within 1–100 ms) and can create an "action potential", a depolarization spike which can rapidly transmit to neighboring cells. The depolarization spike signal travelling from cell to cell can be used to send as a signal to distant groups of cells.

The evolution of the brain: Using such neural circuits, SMs evolved specialized "brains" to perform specific functions. For example, the Jellyfish "brain" is an undifferentiated nerve network, the so- called "nerve net [10]". Using this network, jellyfish detect the presence of other animals and transmit the information to other nerve cells using a circular nerve ring. Another key function of the system is to coordinate the jellyfish swimming motion by opening and contracting its skirt in a coordinated manner.

In contrast, worms have a well defined CNS (Central Nervous System) whose architecture defines a basic design which has remained unchanged from worms to humans. It consists of an anterior brain connected to a nerve cord (shown in Fig. 2 for the earthworm *Lumbricus terrestris)*. Impulses of light, moisture, tough are detected by skin cells and transmitted by a pair of nerve cells in each segment to small ganglia (collection of nerve cells) in the segment as well as to the brain, where the signals are analyzed. The ganglia and the brain then send impulses to muscles to make them respond appropriately. However, the worm "brain" is not the sole "commander" of its nervous system. With its brain removed, worms are able to move, mate, burrow, feed, and learn mazes.

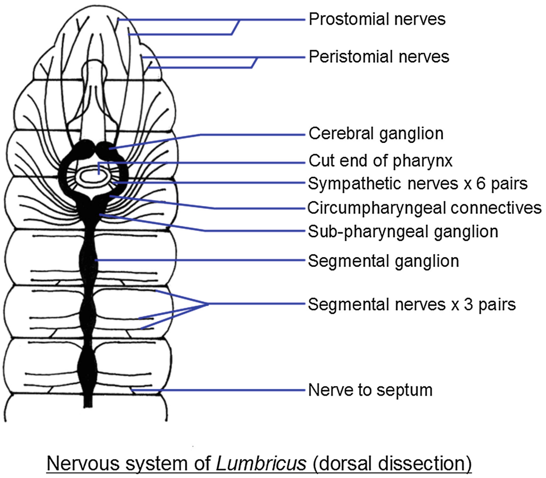

Fig. 2. From http://cronodon.com/files/earthworm_CNS_lateral.gif: The earthworm central nervous system.

Insect brains have a similar pattern. They are giant fiber systems of nerve cells connecting ganglia with a nerve cord running down the body (Fig. 3). The function of the system is to allow rapid conduction of impulses to leg/wing muscles. With more sensory receptors than vertebrates, they are sensitive to odors, sounds, light, texture, pressure, humidity, temperature, and chemicals.

Vertebrates have the most complex brain system. The spinal cord, protected by vertebrae, is now a servant of the brain. The brain itself is a series of swellings, consisting of the hindbrain, the midbrain, and the forebrain. From the hindbrain sprouts a distinctive structure, the "cerebellum" or little brain. Figure 4 shows the basic architecture of the vertebrate brain, which has remained unchanged from fish to humans [11]. The detailed changes in the architecture reflect the changes due to the organism's evolutionary history and the need to perform specific functions in its lifecycle.

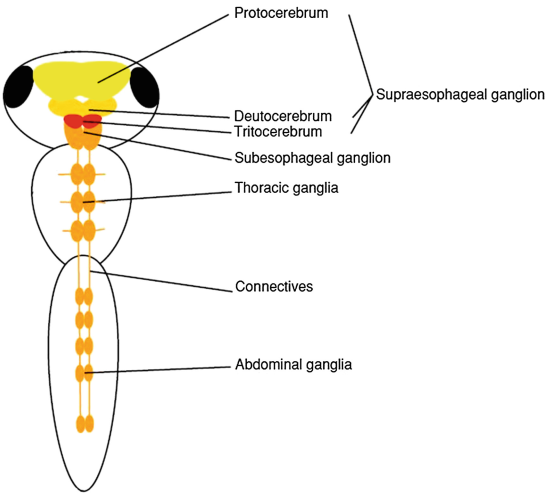

Fig. 3. From: http://bioteaching.files.wordpress.com/2010/05/overall_anatomy.jpg: A prototype of the insect brain.

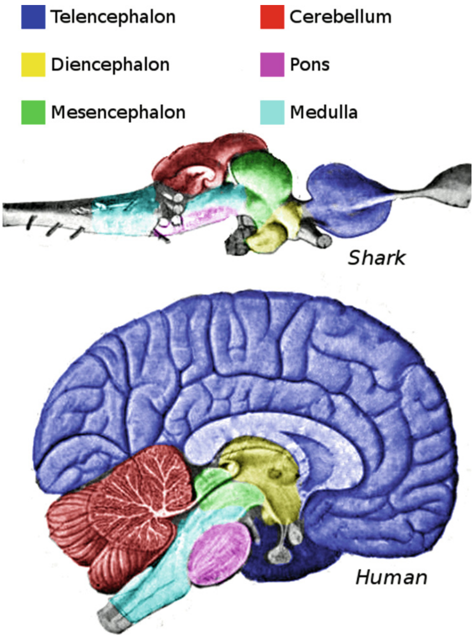

Fig. 4. The vertebrate brain topology is the same in all vertebrates (image from http://en.wikipedia.org/wiki/Brain).

The ancestral cerebrum was two small swellings for smell. In amphibians, there was more gray matter (cell bodies and synapses) between neurons and the cerebrum processed impulses from sensory areas. Gray matter moved outward to the surface to form the cerebral cortex. In some reptiles, the neocortex arose. Mammals, which evolved from reptiles of this type, have the most developed neocortex.

Vertebrate brains have four characteristic features. They have a *centralized architecture,* consisting of a network of structures of nerve cells in the anterior brain, connected to a spinal column. The neuron and sense organ bodies are all located at one end of the organism (*encephalization).* The brain structures are *specialized*, with a greatly increased size and variety of elements compared to invertebrates. Finally, the vertebrate brain has a high degree of *plasticity,* which allows it to learn perceptual and motor tasks and reassign tasks to subunits in response to catastrophic events such as stroke or injury.

The mammalian brain is a simulator [12], which creates a time evolution of events using the sensory inputs from olfaction, sight, touch, hearing, taste and pain stimuli. It regulates posture and locomotion by using a map of the body. It is responsible for our *instincts* and emotions, such as hunger, love/lust/sex, anger, hate/fear, territoriality, possessiveness, dominance/submissiveness, irritability/serenity, parenting etc. It also gives mammals *cognitive capabilities,* such as arousal, attention, thinking, evaluating, insight, abstraction, creativity, choice, purpose, seeking, planning, generalization, judgment, introspection, programming, interest, preference, discrimination, learning, habituation, memory, recognition, retention, knowledge etc.

Consciousness: Although "consciousness" is often believed to be unique to humans and is usually discussed in hushed, reverential tones, it may have appeared in the mammalian brain quite simply, when the brain's "simulation" of the world included a model of itself. This model then allows us to represent the world as a collection of other individuals, some more similar to us than others. Over time, *the representation becomes the reality*, because all of the organism's experiences are tied to the model. The organism is then unable to disentangle itself from the representation and identifies itself as having a "conscience" or "soul" [13].

What needs to be modeled: What does it mean to "understand" how the brain works? Any "model" of the brain should begin by elucidating the architectural, molecular, functional and signaling mechanisms and their evolutionary origins for the following six properties of the brain: 1. Fidelity in entering and exiting states; 2. Ability to interpret sensory input and create appropriate triggers; 3. Ability to recover from error; 4. Robustness to perturbations of sensory inputs; 5. Ability to retain memory of past events; and 6. Plasticity, which gives its subunits the capacity to reassign function [14].

A study of the brain is the ultimate frontier. The brain is an adaptive, dynamic, adaptive system, which simulates the world to allow organisms to learn, survive and replicate. It can only be understood in the context of evolution, as an emergent phenomenon, which uses the underlying architecture bequeathed to it by evolution to create robust, stable, controllable states.

Acknowledgement. None of the work described here is original. In the process of preparing this manuscript, I learned a lot. I am grateful to the Juelich Supercomputing Centre (JSC) at the

Forschungszentrum Juelich for the opportunity to learn from the talks and discussions at the workshop, and for their hospitality and support, which enabled me to attend this workshop. This work was also supported by Grant Nos. NSF PHY11-25915 and NSF Grant #1066293 from the National Science Foundation, the Kavli Institute of Theoretical Physics at UCSB. I thank the Aspen Center for Physics for their hospitality during the writing of this manuscript.

References

1. Dalrymple, G.Brent: The age of the Earth in the twentieth century: a problem (mostly) solved. Spec. Publ. Geol. Soc. Lond. **190**(1), 205–221 (2001). doi:10.1144/GSL.SP.2001.190.01.14
2. Schopf, J.W., Kudryavtsev, A.B., Czaja, A.D., Tripathi, A.B.: Evidence of Archean life: stromatolites and microfossils. Precambrian Res. **158**, 141–155 (2007)
3. Schopf, J.W.: Fossil evidence of Archaean life. Philos. Trans. Roy. Soc. Lond. B Biol. Sci. **361**(1470), 869–885 (2006)
4. Miller, S.L.: Production of amino acids under possible primitive earth conditions. Science **117**(3046), 528–529 (1953). doi:10.1126/science.117.3046.528. PMID 13056598
5. Miller, S.L., Urey, H.C.: Organic compound synthesis on the primitive earth. Science **130** (3370), 245–251 (1959). doi:10.1126/science.130.3370.245. PMID 13668555
6. Forster, A.C., Symons, R.H.: Self-cleavage of plus and minus RNAs of a virusoid and a structural model for the active sites. Cell **49**(2), 211–220 (1987). doi:10.1016/0092-8674(87)90562-9. PMID 2436805
7. Johnston, W., Unrau, P., Lawrence, M., Glasner, M., Bartel, D.: RNA-catalyzed RNA polymerization: accurate and general RNA-templated primer extension. Science **292**(5520), 1319–1325 (2001). doi:10.1126/science.1060786. PMID 11358999
8. Dawkins, R.: The Selfish Gene, 30th Anniversary Edition. Oxford University Press, Oxford (2006). ISBN-10: 0199291152; ISBN-13: 978-0199291151
9. Lane, N.: Power, Sex, Suicide: Mitochondria and the Meaning of Life. ISBN-10: 0199205647; ISBN-13: 978-0199205646. ibid. Life Ascending: The Ten Great Inventions of Evolution. ISBN-10: 0393338665; ISBN-13: 978-0393338669
10. Satterlie, R.A.: Neuronal control of swimming in jellyfish: a comparative story. Can. J. Zool. **80**, 1654–1669 (2002). doi:10.1139/z02-138
11. Shepherd, G.M.: Neurobiology. Oxford University Press, New York (1994). ISBN: 9780195088434
12. Eagelman, D.: Incognito: The Secret Lives of the Brain. Pantheon Books, New York (2011). ISBN-10: 0307389928 | ISBN-13: 978-0307389923
13. Harris, S.: The End of Faith: Religion, Terror, and the Future of Reason. W. W. Norton, New York (2004). ISBN-10: 0393327655; ISBN-13: 978-0393327656
14. Doidge, N.: The Brain That Changes Itself: Stories of Personal Triumph from the Frontiers of Brain Science. Penguin Books, New York (2008). ISBN-10: 0143113100; ISBN-13: 978-0143113102

http://www.springer.com/978-3-319-12083-6

Brain-Inspired Computing
International Workshop, BrainComp 2013, Cetraro, Italy, July
8-11, 2013, Revised Selected Papers
Grandinetti, L.; Lippert, Th.; Petkov, N. (Eds.)
2014, X, 213 p. 83 illus., Softcover
ISBN: 978-3-319-12083-6