A Brain Inspired View of Life: The Scientific, Social and Cultural Implications of Interconnectivity and Complexity

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***Abstract*— Many scientists have tried to identify how the brain creates a working information processing system through its network of neurons, also called the *Connectome* [1]. Two massive brain research projects along with other smaller scale ones have shown that it is not the neurons themselves but the way they are interconnected that gives the brain its computing power. Such complexity and integration is increasingly found in other research areas, due in large part to the progress made in the computational, network and complex systems sciences. I propose that advances in brain research, when viewed together with advances in other areas involving complex systems, can teach us a great deal about the essence of life, and may thus have significant social and cultural implications. The idea that life is made up of integrated information systems or one large, interconnected whole could be the simplest, most elegant explanation of how complexity and integration manifest in humans, nature and in society, and could form the basis of how and why the well-being of each and every single living thing on this earth should matter to all of the rest. Recognizing that science and technology create tools that can be used for social change, the current paradigm shift in science from the parts to the whole and now to interconnectedness implies that we must approach the interconnected and interdependent problems afflicting the world today from a new perspective.**

Keywords—connectome, brain, complexity, dynamic systems, science, technology and society, cognitive systems.

I. Introduction

The brain is an information processing and creating network that makes choices and responds to 'life'. Information flows through the brain in the form of electrochemical rivers that are in a constant state of recreation, forming what is called the connectome [1]. Two large scale projects, the Human Connectome Project (HCP) [2] and the Human Brain Project (HBP) [3], which are trying to map this interconnected whole, have contributed to a new understanding in scientific research, one which emphasizes the network and the relationships within it rather than the parts.

The implication of these projects when viewed together with other recent discoveries in science mentioned in the coming sections is that there are similarly complex layers and levels of interconnectivity in unrelated phenomena that could be seen as chaotic but that simply require new mathematical models. Not only do these complex systems embody the idea that the whole is larger than the sum of the parts, but considered altogether, they themselves could conceivably be reflective of a larger whole. Such a view could lead to a new understanding of life that should inform how cognitive computing, Artificial Intelligence and science in general will shape 21st century culture and society.

II. Interconnectivity in the Brain: Science Goes from Deduction to Induction to Interconnectivity

After Cajal [4] drew the first neuron in 1903, brain research moved away from deduction and began working through induction, or investigating the piece in effort to better understand the whole. Within the neuron doctrine [5], neuroscientists have tried to understand the neuron to understand how the brain works. It is known that one neuron is in connection with 10-15,000 other neurons through synapses [6], all of which results in creating the mind. Thus, the brain, which used to be defined as the organ that established homeostasis [7], is now seen as the organ that creates the mind. Deeper insight into how these 86 billion neurons [8] are interconnected, creating a mathematical probability network that contains $2^{86\text{billion}}$ alternatives in the brain, might contribute to the debate about whether and how living things are interconnected.

The Human Connectome Project (HCP), which began in the US in 2009, aims to map the neural network to elucidate the anatomical and functional interconnectivity of the healthy human brain to create data that would support research into conditions such as dyslexia, autism and Alzheimer's disease [2]. The data obtained through the cooperation of dozens of researchers are available to the public on an internet based neuroinformatics platform [2]. Europe's response to the same research goal, but from a more mathematical perspective, the Human Brain Project (HBP) was initiated within the EU in 2013 [3]. As one of the largest collective efforts to explain the brain, the HBP tried to understand how information flows through it and whether a supercomputer can be built that can simulate the human brain. The project involved the most sophisticated computers with an eye to building a scientific research platform for scientists all over Europe in fields related to neuroscience, information processing and neuroscience.

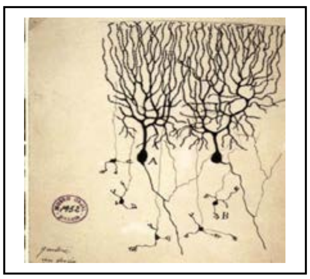

Fig. 1: Cajal's drawing of the neuron.

The first results of the HBP work were published in 2015 [9], revealing data about the interconnectivity, not in the 86 billion neuron human brain, but in a 31,000 neuron section of a rat brain. While it turned out that achieving a simulation of the human brain within a decade was unachievable as a goal, the project underlined the premise that Big Data would be a crucial part of discovering how the brain truly works. This showed that further development was necessary in the field of network sciences, mathematics and computerized network sciences.

One factor that renders the brain difficult to understand is that it consists of ever-changing patterns. An analogy might help describe these patterns in the connectome referred to as neuroplasticity [10]; let us consider a satellite image of the Amazon River delta. The Amazon delta looks different every year, depending on climate conditions, the effects of human activity, (de)forestation and so on; thus the network never looks the same. In our brain, as well, information flows in the form of electrochemical rivers, and these rivers flow in different patterns from one moment to the next. The more a river flows, the deeper its river bed gets; or in the case of the brain, the more it is used, the more pronounced a given neural pathway becomes. The pattern at any given moment only exists within that moment; it has never been the same and it never will be.

Such constant change and complexity makes it extremely challenging to examine each neuron individually, so scientists simplify them into clusters based on function to examine these electrochemical rivers. In Fig. 2, in the top picture, there is a cadaver and on the bottom is the MR image of the same area after that same region has been operated on. Each fiber is an electrochemical river made up of about 200 to 300 million neurons. This shows the flow of information. Therefore, function also forms anatomy. But a look into the system made up of the neurons would offer a much more detailed image than this. Each fiber here is actually merged functional units.

Fig. 2: Cadaver brain on top and MR image of same area post-operatively following the resection of a tumor on the bottom (Photo: BAU School of Medicine).

Fig.3 A hypothetical map of the flight routes of all planes in an airline company

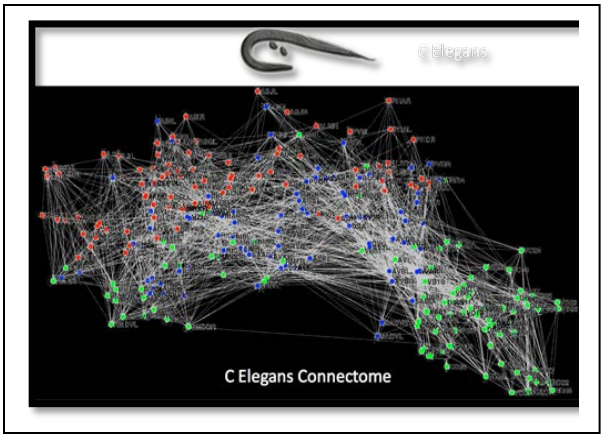

Fig. 4: The mapped connectome of the C Elegans Worm [11]

So then what is the relationship between a neuron and the connectome? In simple terms, the relationship could be likened to the relationship between an airline company and an airplane. Let us assume that there are 326 airplanes in the Turkish Airlines company. A total of 326 airplanes individually sitting in warehouses do not make up an airline company. But using intelligence to organize these in a certain way to fly from one city to another, with knowledge of the location and destination of a plane at any given time would constitute an airline company.

In a Nobel prize winning work from 1986, the connectome of a worm was mapped [11], finding 383 neurons. In the above mentioned analogy, the planes represent each single neuron, while the interconnectivity map of all of the flights represents the entire connectome. In the study on the worm, the scientists incapacitated each neuron in turn, and were able to see the different decisions the worm made and how its life changed. Therefore, how each individual neuron affected this worm's connectome was found. It is this connectome that creates these choices that the worm makes and therefore the life it lives. Assuming there were nine of these worms, eight might choose go toward a source of fructose whereas one might choose to move toward a breadcrumb that fell off the table. What causes one worm to make a different decision than the other worms is the pattern of the information network of its connectome. By taking the definition of consciousness, a somewhat elusive term, as the ability to make decisions; it might be fair to say that the connectome creates consciousness. Once the connectome is mathematically modeled, that model might also be used as the mathematical model for explaining the conscience. The above example of the model with 383 neurons makes it even more compelling to understand a decision making system made up of 86 billion neurons.

Chosen the Nature Method of the Year in 2015 [12], the novel field of optogenetics combines genetics and optics to identify the functions in the connectome. In a recent experiment [13], some genes were implanted into a rat brain to stimulate or inhibit a part of the amygdala, thereby modifying the connectome of the rat so that it does not respond to food even when it is hungry or does respond to food when it is not. An exciting implication of this field of research for brain surgeons such as myself, is that the mapping of the connectome structure of, for instance, a meningioma tumor, as the next step of the research we have been doing [14], could one day make connectome surgery a viable treatment modality. This will only be made possible once the mathematical modelling of such complex structures of interconnectivity is advanced enough. Even so, our deeper current understanding of neurons and the patterns of interconnectivity they work in; i.e., neuronal networks, through studies such as this has fueled advances in artificial intelligence research, and vice versa [15].

III. INTERCONNECTIVITY IN OTHER PHENOMENA

We now understand that information flows in the brain in much more complex, ever-changing patterns modified by learning, experience and growth/aging. While there may be differences at the micro level, at the macro level similar interconnectedness and adaptive complexity patterns [16] have recently been discovered in fields such as mathematics, medicine, astrophysics, biology and even social science. In many instances, what was thought of as chaotic can now be mathematically modelled. Such complexity models and advanced mathematical models have been useful for understanding helium [17], how societies interact [18] and angiogenesis [19], just to cite a few. Taken altogether, these should have significant implications for our view of ourselves in relation to life and for society and culture, as the next section will discuss.

In the field of astrophysics; scientists have managed to identify the supercluster that houses our galaxy, the Milky Way, naming it *Laniakea* (meaning 'immeasurable heaven' in Hawaiian) [20]. This was made possible by an investigation of the interconnectivity among galaxies and again, the ability to mathematically model them, based on their peculiar velocity and their relation to all of the other surrounding superclusters.

As for the field of genetics; five decades after the DNA helix was discovered by Watson and Crick [21], in 2003, the Human Genome Project [22] was completed and DNA was mapped. It was previously thought that humans have about 2 million genes. After a few years, the estimate was brought down to about 1 million, then later to 200,000 genes. In fact, it is now known that humans have about 20,000 genes [23]. Once the genome had been mapped, it was thought that the genetic basis and cures of all illnesses afflicting humans would be discovered. Nevertheless, the important discovery of epigenetics [24] has shown that this

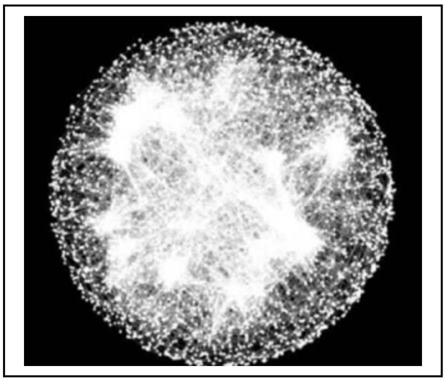

Fig 5: A global genetic interaction profile similarity network. A screenshot of TheCellMap.org home page [27]

was a gross oversimplification and that there are many more variables involved. The impact of external factors is now taken into consideration and genes are not seen as absolutely predictive of illnesses or other characteristics, such as appearance. As an example, the twin girls featured in the National Geographic April issue on Race [25] are actually identical twins, but look as if they were from different races different due to epigenetic changes. Considering that even a banana has a little over 36,000 genes [26], it can be concluded that it is not how many genes we have but the interconnectivity of these genes, as well as the plethora of outside factors, that differentiates living things from each other. Just as brain scientists working on the connectome are collaboratively trying to understand the complexity of the neural network using common data and mathematical modelling platforms, so are genetics researchers. TheCellMap.org [27] is one such site by researchers that offers complete access to a significant amount of quantitative genomic data on brewer's yeast. Fig. 5 is a screenshot from their interactive webpage where users can choose which genes they would like to see interacting. Once again, it is the interactions among genes and not the genes themselves that take center-stage.

Another example highlighting the idea of the interconnected whole could be cited jointly from biology and physics. The human body is made up of 37 trillion cells [28]. It was back in 1953 that a physicist called Dr. Paul C. Abersold [29] put forth that "in a year approximately 98 percent of the atoms in us now will be replaced by other atoms that we take in in our air, food, and drink." In other words, the atoms and molecules that make up our cells are replaced after a certain time. In an open database called Bionumbers, created by systems biologists from Harvard, it is shown that, for example, stomach cells replace themselves in 2-9 days and platelets in 10 days [30]. Despite all of this replacement, a person remains the same person. This implies that what is consistent is the communication among those molecules and atoms, not just the particles themselves, resulting in a larger whole.

Our new understanding of communication or interconnectivity among the parts resulting in seeming chaos but actually creating order is a theme found also in a recent experiment on starling flocks [31]. Consider a group of birds simply perched on an electrical line; i.e., stationary and literally linear, as compared to our new understanding of the behavior of a flock of starlings making strikingly elegant and well-coordinated 'nonlinear' dynamical maneuvers as a group. It used to be thought that such movements were chaotic and disordered. To the contrary, we now know that information transfer takes place among the members of the flock and can be accurately explained using equations of superfluidity [31].

Sensing something inherently different about living things as compared to inorganic matter even though they also consist of molecules and atoms, Schrödinger [32] posed his famous question, 'What is Life?' in 1943 and brought up biology framed within a physics question. He wondered how the inorganic universe could create the organic universe in violation of the second law of thermodynamics and said the physics underlying biological systems needed to be discovered. Russian physicist Ilya Prigogine worked on answering this question in the 1980s. He came up with a concept that reconciled thermodynamics and self-reorganization in complex systems, stating that deterministic theory does not apply to 'irreversible' systems such as evolution, the weather and solar radiation [33]. Due to self-reorganization, the interaction among the parts in such complex systems as these results in a whole that is larger than the sum of its parts. This complemented what Maturana and Varela had termed autopoiesis; i.e., self-organization, as a way to distinguish living things from non-living things, referring to the parts in a system interacting among each other and reorganizing themselves within closed systems [34].

Life, as an open system, can perhaps be explained with the idea underlying Emergence Theory [35], which states that the interaction among the parts of a whole results in changing the whole such that its characteristics are different than those of the parts. Here are very interesting examples for this: The first concerns an organoid grown in a laboratory in the US [36]. Researchers triggered stem cells to become brain cortex cells and monitored the electrical activity among the cells. The EEG recordings after 6 months showed the same level and type of activity emitted by brains of babies born 25-39 weeks after they were conceived. This is remarkable because the cells began interacting in ways beyond what they were initially programmed to do. The second example concerns AI. Facebook programmed two AI robots to communicate with each other, but after a certain amount of time, the robots created and began to use a language that the programmers had not programmed them to use and that was incomprehensible to the programmers [37].

Such discoveries have also been made in the social sciences through the integration of natural sciences, social sciences, cognitive computing, network science and Artificial Intelligence. One example of this integration is the Yale Institute for Network Science, which houses the Human Nature Lab. Just the fact that a Human Nature laboratory is established within an institute for network science is tremendous. The team there, interested in the emergent properties of social systems, has conducted remarkable research using network science models to investigate social contagion, focusing on such diverse topics as obesity, happiness and health outcomes [38]. Among the many examples showing the interconnectedness in society is their finding that the biological and behavioral trait of obesity seems to spread through social ties [39]. Another interesting study examining networks looked into the terrorist organization ISIS and how it spread propaganda over the social media network, its main recruitment and motivation tool [40]. The study found over 22,000 Twitter users whose behavior on the platform contributed to supporting the group to varying degrees. As we learn more about the interconnected nature of social phenomena using the tools offered by cognitive computing, we are bound to see the development of interventions.

IV. THE IMPLICATIONS OF INTERCONNECTIVITY FOR SOCIETY AND CULTURE

Extrapolating from the idea of interconnectivity and the existence of complex systems everywhere in society, nature, the universe and life, as the largest information processing system, what emerges is the importance of connections, relationships and context rather than parts. The recent discoveries mentioned above, taken together with our experience that scientific advances ultimately change society and culture, and the shift in science from an emphasis of the part to the interconnected whole (Table 1) have important implications for us as a global community.

Culture and society are built upon common values, beliefs and knowledge. Although these take time to change, history has shown that they do so gradually. Science and technology offer the tools that can be used to change culture and the organization of society-tools which must be developed with great care for the good of society. The opportunity humanity has today is this paradigm shift we are undergoing, which could change how humans see ourselves – from individual and independent towards part of an interconnected whole. Most of the problems the world is faced with today can be traced back to not seeing ourselves as part of a greater whole. As Capra and Luisi [41] state, in their attempt to convince us that we need to recognize the interconnectedness of the challenges afflicting global society today, these problems "cannot be understood in isolation" and are interconnected and interdependent.

I agree with the idea that life should be viewed as a unity of systems and would, in fact, like to take this one step further. As we learn more about complex systems and the way information is encoded in them, we understand the interesting ways they are layered and coexist. Genes are a great example. When DNA was discovered, it was not yet known that the DNA-RNA-protein pathway was reversible. DNA can in fact be obtained from RNA, and RNA from proteins. One of the most striking examples of this is a study that utilized the principles of bacteria adaptation as well as information storage in order to make the DNA of bacteria archive real data [42]. The scientists uploaded the pixel values of an animation-the GIF of a galloping horse- into the genomes of a population of living bacteria via a virus. Later the information was re-transformed into a GIF, in the form of the second image, eerily similar to the initial one. Whether it is the base-22,000 genome, base-26 alphabet, base-2 digital language, base-4 DNA or RNA, base-10 algebra, or base-86 billion connectome, all of these are ways of encoding information and the same information can be encoded or decoded into or from any one of these coding systems. As we learn more about the interactivity among the parts of information processing networks, and develop our mathematical models to do so, we are bound to discover more about how each can be transformed into the others. Such transformations, in my opinion are key to uncovering the way living things, including how humans and societies are connected.

TABLE 1

Fundamental Shift in Science: From Parts to Interconnectivity	
Bacon, Descartes, Newton (1600+)	Laniakea, Epigenetics, Connectome (1905)
Reality is a machine made up of the sum of measurable, individual pieces.	Reality is a web of inseparable interconnections The whole is greater than the sum of its parts.
Determinism	Probability
Dialectics	Interconnected Wholeness
Cartesian thought	Interconnectivity, Network thinking
Body-Mind-Consciousness Separation	Body-Mind-Consciousness Wholeness
2^{nd} Law of Thermodynamics *Newton, Carnot, Joule*	Autopoiesis, Self-organization, Emergence *Maturana, Varela, Prigogine*
Scientific experiments are independent of the observer	Scientific observations are dependent upon the observer and the information gathering process
The goal is to establish control over the process or object studied.	The goal is to become involved in the process studied and to coexist.

Although societies have interacted with each other since the beginning of human existence, today's level of connectivity is unprecedented. Not only is this connectivity resulting in new cultural, social and political practices, it has enabled scientists to collaborate like never before. The HCP and the HBP, the large scale brain research projects I mentioned, are only two examples of this. With ever larger sets of Big Data analyzed by more complex algorithms, we will see cognitive computing tools used to an even greater extent.

Today, more than ever, we need to recognize the need for new ethics based on a new social theory that emphasizes context, interrelations and interdependence to inform the work being carried out in cognitive computing and Artificial Intelligence if we are to resolve such pressing issues as climate change and inequality. Awareness must be raised among the scientific community working on cognitive computing and AI about the inevitable causal links among societies and phenomena, and encourage them to collaborate with researchers from other fields to better foresee the possible consequences of their work. Naturally, there will be the challenges regarding the ethical use of big data, discussions around responsibility and the policymaking keeping up with scientific advances, but different versions of such problems have been dealt with for centuries.

To conclude, I would propose that just as we are newly discovering the complexity of the brain, flocks of starlings, genes and epigenetic effects, social contagion among other phenomena, one day, a mathematical model that explains the interconnection among all living things will be discovered. There is no doubt that this will be done through the increased capability of cognitive computing and network and systems sciences. At first glance, a connection that ties together everything in the universe may seem like an outlandish idea, but I am not the first to propose unity and interconnectedness among all things on a more elemental level. Many philosophers, poets and even religions have already done so. All we need now is scientists from all domains, including cognitive computing, natural sciences and social sciences to consider what part they play in the grandest scheme of things.

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