BCI Quantum Computing IPLD for Brain

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B/CI: Quantum Computing, Holographic Control Theory, and Blockchain IPLD for Brain

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Abstract

In the concluding part of this book on nanomedical brain/cloud interface (B/CI) technologies, the current chapter considers the greater impact of these advances on humanity. For the general realization of the B/CI and especially for B/CI cloudminds (minds safely connected to the internet cloud via B/CI for interactive purposes), a robust hardware and software solution is needed. This work proposes quantum computing as the hardware platform for the B/CI, together with a holographic control theory (based on the AdS/CFT correspondence) as the lever for macroscale control of the quantum computing cloud environment (the AdS/CFT correspondence is a universal control theory to orchestrate macroscale-quantum domains), and a bio-blockchain neuroeconomy as the operating software of the in-brain B/CI neuronanorobot network. Recent advance in quantum theory (MERA, SYK, and tensor network models) may have a biophysics interpretation in the AdS/CFT dual of the neuron-synapse system defines as bio-correspondence, holographic synapses, and neuronal gauge theory, implemented through quantum machine learning. Overcoming hindrances to large-scale group collaboration is addressed to elaborate peak performance cloudminds. The proximate objective of the B/CI is to map, monitor, cure, and enhance neural activity. At the more abstract level of everyday reality, the purpose of the B/CI is to facilitate human productivity, well-being, and enjoyment. The stakes of B/CI cloudminds are making progress towards the achievement of a Kardashev-plus society that is able to marshal all tangible and intangible resources by mental and physical means.

Keywords: brain/cloud interface, cloudmind, direct neural transfer, quantum computing, blockchain, AdS/CFT correspondence, holographic principle, neuromorphic architecture, biophysics, control theory, payment channels, Kardashev civilization

14.1 B/CI Cloudmind

14.1.1 BCI Technologies

The aim of this chapter is to provide a detailed vision of how the cerebral cortex of the human brain might be safely, securely, and seamlessly integrated with the cloud, being manifest as a brain/cloud interface (B/CI) cloudmind for deployment in a collaborative context. There are two different classes of BCI technologies (Figure 1). First is the core BCI (brain-computer interface) which exists and allows individuals to use electrical brain waves to control prosthetic limbs and computer cursors. Second is the B/CI (human brain/cloud interface) which is a future technology to interface the human brain with the internet cloud on an individual and group basis.

BCI Technologies	Functionality
Core BCI	Prosthetic limb and cursor control
Cloudmind B/CI (individual and group)	Productivity, well-being, and enjoyment

Figure 1. BCI Technology Platforms and Functionality.

14.1.1.1 BCI (Brain-Computer Interface)

The core technology is the BCI (brain-computer interface). A BCI or brain-computer interface is a direct communication pathway between a wired brain and an external device (Nicolas-Alonso et al., 2012). Electrical brain waves are used to direct external behavior via EEG (electroencephalography). One of the first demonstrations of a BCI was in 1988, to control a robot (Bozinovski et al., 1988). BCIs may include neuroprosthetics such as cochlear implants (220,000 of which had been implanted worldwide as of 2010 (NIH, 2011)).

14.1.1.2 B/CI (Human Brain/Cloud Interface)

The proposed technology is the B/CI (human brain/cloud interface) to safely connect the human brain with the internet cloud (Martins et al., 2019). Such a B/CI would be based on neuronanorobotics (medical nanorobots specifically designed to operate in the brain).[1] Fleets of such neuronanorobots would comprise the B/CI, having controlled connectivity between neural cells and external data storage and processing. One of the first objectives of the B/CI is to monitor the brain's 86 billion neurons and 200 trillion synapses for health purposes.

14.1.1.3 B/CI Cloudmind

A cloudmind is one or more minds connected to the internet cloud (Swan, 2016, 2019). A cloudmind might be comprised of an individual mind operating on the internet, or multiple human and machine minds participating in an interactive collaboration. 'Mind' generally denotes an entity with processing capability (not necessarily a biological mind that is conscious). An individual or group cloudmind might pursue a variety of activities related to productivity, well-being, and enjoyment. Minds are interfaced to the internet cloud through the B/CI (network of neuronanorobots). By linking brains to the internet, B/CIs could allow individuals to be more highly connectable not only to communications networks but also to other minds, which could enable new kinds of learning and interaction. The term cloudmind might also be used to refer to industrial robotics coordination networks of cloud-connected smart machines (Keenan, 2017), and brainets as other forms of human or animal cloud-connected minds (Martins et al., 2019, 8).

[1] Brain-based nanorobots are referred to as "neuronanorobots" and also "neuralnanorobots" (Martins, 2016, 2019)

14.1.2 B/CI, Medical Nanorobots, and Neuronanorobots

The B/CI is comprised of neuronanorobots, a network of medical nanorobots designed to operate in the brain. Medical nanorobots are nanoscale molecular machines (1 x 10^{-9} m) that have been proposed to complement native cells and perform medically-related tasks in the body. Several species of medical nanorobots have been articulated such as respirocytes (artificial red blood cells), clottocytes (artificial platelets), and microbivores (artificial phagocytes) (Freitas, 2000, 2005, 2012). The estimated size of each medical nanorobot is about 1-3 microns (1,000-3,000 nm), with even smaller parts, on the order of 1-10 nm (Freitas, 2012, 69). Such medical nanorobots would patrol the body for health monitoring and intervention (Fahy & Wowk, 2015).

Three species of neuronanorobots have been articulated to correspond to the different phases of neural signaling: axonal endoneurobots, synaptobots, and gliabots (Martins et al., 2019). Axonal endoneurobots would align with the neuron's axon transmission of the electrical action potential, synaptobots would aid in the signal transmission across the synaptic cleft between neurons, and gliabots would support the glial cells that facilitate neural signaling. For delivery, neuronanorobots would need to traverse the blood-brain barrier, enter the brain parenchyma, ingress into individual human brain cells, and automatically position themselves at the axon initial segments of neurons (endoneurobots), in proximity to synapses (synaptobots), and within glial cells (gliabots) (Martins et al., 2019). The full B/CI would consist of a one-to-one co-positioning of neuronanorobots with human brain cells (Martins et al., 2012, 8).

14.1.2.1 B/CI Applications: Map, Monitor, Cure, and Enhance

Four levels of B/CI applications can be outlined as map, monitor, cure, and enhance neural activity (Figure 2). In order to monitor the brain, the first step necessitates mapping the connectome. Connectome mapping is creating a wiring diagram of the the entire structural and functional information of the brain in proper temporal and spatial resolution (Martins et al., 2016). A high-resolution digital connectome-based map of the brain suggests that an individual brain can be simulated, including for functional, health-related, and enhancement purposes. (The current state-of-the-art connectome research is the 3D mapping of the mouse brain at single cell resolution in the Allen Mouse Brain Atlas project (Wang et al., 2020)). Second, with the digital connectome, the next phase of monitoring could take place. This might include the tracking and communicating of information, initially issuing alerts and conducting daily health checks, and later backing up memories. The third phase is cure, facilitating diagnosis and cure for the approximately 400 conditions that affect the human brain. Cure might entail restoring lost or damaged functionality (particularly related to neurodegenerative disease and senescence). For example, to combat stroke, neuronanorobots might provide directed electrical stimulus to the brain to dissolve blood clots using ultrasound (Marosfoi et al., 2015). The farther-reaching potential of the B/CI is indicated in the fourth phase of enhancement applications that could accentuate neural activity related to learning, attention, and memory.

B/CI Function	Neural Activity Objectives and Tasks
Map	Connectome mapping to create a wiring diagram of the brain
Monitor	Direct monitoring of the brain's 86 billion neurons and 200 trillion synapses
Cure	Acute and chronic disease response, restoring lost or damaged functionality
Enhance	Enhance neural activity related to learning, attention, and memory

Figure 2. B/CI Applications: Map, Monitor, Cure, and Enhance Neural Activity.

The B/CI, and medical nanorobots more generally, can be seen as a third on-board ecosystem. The human organism already consists of the underlying human cells plus the microbiome (Yong, 2016), and nanorobots would be an additional on-board ecosystem devoted to health monitoring, disease cure, and enhancement. The job of the nanorobot ecosystem would be to provide a protective buffer between the body's biological health and its environment.

14.1.3 Purpose of B/CIs: Kardashev-plus Society

This section addresses the question of why B/CIs are needed. The proximate objective of B/CIs as a health-related tool to map, monitor, cure, and enhance biological capabilities is clear. However, the question arises as to what B/CIs mean from a more abstract level of human potentiality. An argument can be made that B/CIs are not just nice, but necessary to keep pace with the scale and complexity of modernity. The world has been evolving at an accelerated rate and the capability of the human brain to keep up has lagged. New methods of understanding, learning, and coordination are needed. For example, B/CIs might enable direct neural transfer (transferring information directly into the brain) as a means of heightened learning (Martins et al., 2019, 15). The overall aim of B/CIs can be seen as being parallel to that of science and technology, whose general purpose is to contribute to the productivity, well-being, and enjoyment of society. Such a tripartite objective can likewise be the goal of B/CIs. The reason to implement B/CIs is to produce lives that are more meaningful, rewarding, and fulfilling. B/CIs are just one of many possible tools and technologies that could be deployed towards the overall objective of the long-term surviving and flourishing of society.

14.1.3.1 Kardashev Civilizations

A large-scale vision for the progression of society is Kardashev civilizations. Developed by Soviet astrophysicist Kardashev in 1964, the schema describes a society's ability to control energy-related resources, and defines three levels of advancement (Figure 3). A Type I planetary society is able to use all the energy of the sunlight that falls on the planet. A Type II stellar civilization is able to use all the energy that the sun produces. A Type III galactic civilization is able to use the energy of the entire galaxy. In terms of contemporary progress, one estimate is that humanity has attained a Type 0.7 civilization and might advance to Type 1 within 100-200 years if energy consumption were to increase 3 percent each year (Kaku, 2018, 250).

Civilization	Energy Marshaling	Energy Consumption	
Type I: Planetary Civilization	Use all the energy of the sun that falls on the planet	10^{16} W	≈4×10^{19} erg/sec (4×10^{12} watts)[2]
Type II: Stellar Civilization	Use all the energy that the sun produces	10^{26} W	≈4×10^{33} erg/sec (4×10^{26} watts) Luminosity of the Sun
Type III: Galactic Civilization	Use the energy of the entire galaxy	10^{36} W	≈4×10^{44} erg/sec (4×10^{37} watts) Luminosity of the Milky Way

Figure 3. The Kardashev Scale: Technological Advancement of Civilization by Energy Marshaling.

14.1.3.2 Kardashev-plus Society

Kardashev's vision of the ability to control energy resources is well-taken and can be expanded more generally to the notion of a Kardashev-plus society. A Kardashev-plus society is one that is able to marshal *all* resources, tangible and intangible, not only energy as a central

[2] The erg (Greek *ergon*: work, task) is a unit of energy equal to 10^{-7} joules in the centimeter-gram-second system of units. Erg/sec is a unit of energy or work per second.

resource, for society's long-term flourishing. To reach a Kardashev-plus society, new models, techniques, and strategies such as B/CIs are necessary. Tools adequate to carrying out a new tier of very large-scale projects beyond today's megaprojects[3] are needed. The B/CI is indicated as a workhorse tool for coordinating both mental and physical resources on a beyond-planetary scale.

14.1.3.3 Theoretical Model Development

The thesis of this work is that B/CIs constitute a next-generation technology for realizing a Kardashev-plus society for two reasons. First, B/CIs are necessary merely to keep pace with modern reality. Second, B/CIs enable a new level of capability in coordinated neural activity for controlling a much larger set of resources for societal advance.

A theoretical model of B/CI technologies as a casual approach to achieving a Kardashev-plus society is outlined in Figure 4. The research question that frames this analysis is as follows: How do brain/cloud interface technologies (including individual and group cloudminds) impact the ability to reach a Kardashev-plus Society? The desired outcome (dependent variable) is a Kardashev-plus society. The premise is that B/CI technologies (the independent variable) have a causal influence on the objective. Within B/CI technologies, two factors (moderating variables) may influence the ability of B/CI technologies to produce a Kardashev-plus society, hardware and software. Hence, this work develops a hardware and software approach to B/CI technologies as the means of engendering progress towards the attainment of a Kardashev-plus society.

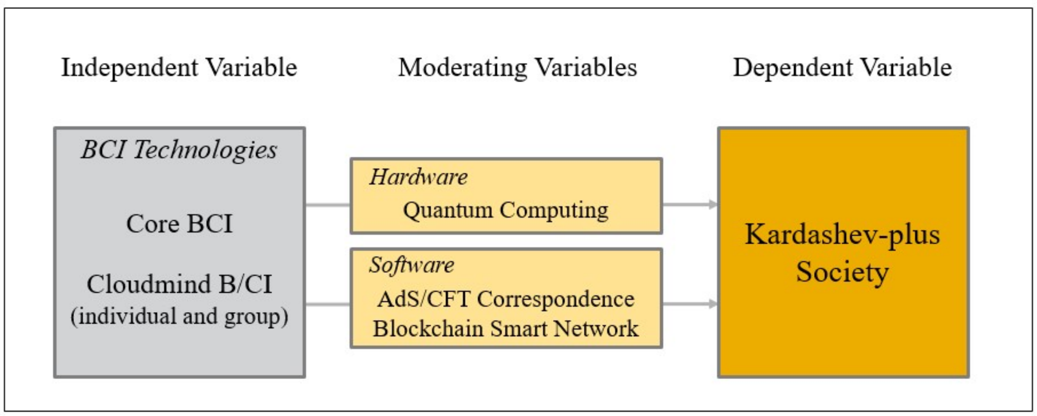

Figure 4. Theoretical Model for attaining a Kardashev-plus Society.

The chapter unfolds in five parts. First, an overview of the B/CI project as the instantiation of neural signaling with neuronanorobots is provided. Second, quantum computing is proposed as the hardware platform for the B/CI. Third, a holographic control theory (based on the AdS/CFT correspondence) is articulated to interface between the quantum computing cloud and the macroscale reality of interacting with the B/CI. Fourth, a bio-blockchain neuroeconomy is suggested as the operating software for the autonomous control of the in-brain B/CI neuronanorobot network. Fifth, the coordinated operation of peak performance cloudminds in group collaboration is addressed. Risks and limitations are considered. The Appendices collect some technical details about neuronanorobot size and B/CI implementation.

[3] Megaprojects are large-scale, complex ventures characterized by a large investment commitment, complexity, and long-lasting impact on millions of people (Brookes & Locatelli, 2015). Examples include bridges, airports, oil and gas extraction projects, hydroelectric facilities, nuclear power plants, and genome sequencing (Flyvbjerg, 2017).

14.2 The B/CI Project: Neural Signaling and Neuronanorobot Instantiation

14.2.1 Summary of Neural Signaling

The human brain is comprised of an estimated 86 billion neurons, 200 trillion synapses (each neuron having ~2,300 synapses), and 86 billion glial cells (Martins et al., 2019). A neuron is an electrically-excitable cell that communicates with other cells by sending a signal called an action potential across specialized connections called synapses. Each neuron is comprised of a cell body (soma), a long thin axon insulated by a myelin sheath for outbound signaling, and multiple dendrites for receiving inbound signals. Glial cells are non-neuronal cells that insulate neurons from each other, facilitate signaling, and supply nutrients.

Neurons have two main processes, sending and receiving signals. To send a signal, an axon transmits information from the neuron to neighboring neurons. To receive a signal, a neuron's dendrites receive information sent by the axons of other neurons. The signaling activity of neurons is both electrical and chemical. The axons of neurons produce and transmit electrical pulses called action potentials which travel along the axon like a wave. The action potential is a short electrical pulse that is 0.1 V in amplitude and lasts for one millisecond (Nicholls et al., 2012, 14). The action potential is sent along the axon to the axon terminals in the synaptic nerve endings, from which the axon contacts the dendrites of other neurons. Synapses (from the Greek word for conjunction) consist of a pre-synaptic terminal on the outbound neuron, a post-synaptic terminal on the dendrites of the receiving neuron, and a 20 nm gap between them (synaptic cleft).

The electrical current responsible for the propagation of the action potential along the axons cannot bridge the synaptic cleft, and so transmission across the gap between one neuron's axon and another's dendrites is accomplished by chemical messengers called neurotransmitters. Various chemical neurotransmitters are stored in vesicles (spherical bags) in the synaptic terminal at the nerve ending to be available for release across the synaptic junction.

At the pre-synaptic terminal (a bulbous area at the end of the neuron), the arrival of an electrical action potential causes voltage-gated calcium channels in the terminal wall to open and disgorge calcium into the terminal bulb. The calcium triggers synaptic vesicles located in the terminal to release their neurotransmitter contents into the synaptic cleft. In less than a millisecond, neurotransmitter diffuses across the gap and activates receptors in the membrane of the post-synaptic terminal (dendrites) in the receiving neuron. Glial cells are present around the synaptic cleft to facilitate signaling and to clean up, for example, by recycling neurotransmitter from the synaptic cleft back into synaptic vesicles (Shepherd, 1974).

Although each neuron has only one axon (which ends in multiple axon terminals for sending signals), each neuron has multiple dendrites for receiving signals. On average, there may be about 2,300 synaptic connections to other neurons (Martins et al., 2019, 1). Other estimates are higher, that each neuron may have an average of 7,000 synaptic connections to other neurons (Finger, 1994). Specialized cells such as the Purkinje cells in the cerebellum have over 1,000 dendritic branches, each with thousands of synaptic connections to other neurons. Synapses can be either excitatory or inhibitory, to reinforce or dampen the signal that comes from the axon.

14.2.1.1 Size and Scale (and Avogadro's number)

Comprehending the B/CI requires thinking in various numeric scales (see Appendix for details and references). Some of the units employed are the micron (µm, a millionth of a meter, 1 x 10^{-6} meter) and the nanometer (a billionth of a meter, 1 x 10^{-9} meter). One micron is 1,000 nm. As a heuristic, the diameter of a human hair is ~100 microns or 100,000 nanometers, and the basic nanorobot is 1,000 nm. A red blood cell is 7,000 nm. Neurons are larger, having a 10,000-25,000 nm cell body, and glial cells are about the same size as neurons, 15,000-30,000 nm. The synaptic terminal is quite small, perhaps only 100-1,000 nm^3, and the synaptic cleft between neurons even smaller at 20 nm. Glial cells are separated from each other by only 2 nm. The nanometer scale (1×10^{-9} meter) is the scale of atoms and quantum mechanics. The atomic scale is used in the atomically-precise molecular manufacturing of nanorobots, and also in quantum computing to manipulate quantum objects (atoms, ions, and photons) in computation.

Estimates of the relative size of the different populations of neural cells is presented in Figure 5. Of the estimated 86 billion neurons in the brain, the 16 billion neurons in the cerebral cortex may be of primary interest to the B/CI as they are associated with higher-order functions such as planning, reasoning, and vision.

Entity	**Size Estimate**			**Reference**
Neurons	86×10^9	86,000,000,000	86 billion	Martins, 2019
Cerebellum (80%)	69×10^9	69,030,000,000	69 billion	Azevedo, 2009
Cerebral cortex (19%)	16×10^9	16,340,000,000	16 billion	Azevedo, 2009
Glial cells	86×10^9	86,000,000,000	86 billion	von Bartheld, 2016
Synapses	2×10^{14}	200,000,000,000,000	200 trillion	Martins, 2019
Avogadro's number	6×10^{23}	600,000,000,000,000,000,000,000	0.6 trillion x 1 trillion	Nelson, 2008, 20

Figure 5. Size of Neural Cell Populations in the Human Brain.

Although 86 billion neurons, 86 billion glial cells, and 200 trillion synapses are large numbers, this might be manageable when seen in the overall context of the human body and the routine processing capabilities of data analytics. A "really large number" in biology and chemistry is Avogadro's number, a trillion trillion (more specifically (6×10^{23}) or (0.6 of a trillion × a trillion)), which is used to refer to molecular volumes. One first step with B/CIs could be logging and tracking the billions and trillions of neurons, glial cells, and synapses. The next steps may involve modeling their activity which is more on the order of Avogadro's number. Quantum computing is envisioned to operate at the scale of Avogadro's number.

A quantum computer with 79 entangled qubits (systems currently have 20 qubits) has an Avogadro number of states (with quantum entanglement, n qubits represent $2n$ different states on which the same calculation can be performed simultaneously). Such capacity is indicated in large-scale computation environments (similar to that required by the B/CI) such as particle accelerators. CERN for example contemplates computation at the scale of Avogadro's number in the next upgrade of the LHC, the High-Luminosity Large Hadron Collider (HL-LHC), expected to begin operation in 2026, with an estimated required computing capacity 50-100 times greater than what currently exists (Carminati, 2018).

14.2.2 Neural Cells and Neuronanorobot Complements

Three neuronanorobot species have been proposed to correspond to the different phases of neural signaling, at the cellular processes of neurons and the sub-cellular processing of synapses. A one-to-one relationship is envisioned for pairing each neuronanorobot with the neural cell to which it corresponds (Figure 6). Axonal endoneurobots relate to the axon and its function of sending action potentials as outbound signals. The neuronanorobot may be located in the cell body (soma) at the beginning of the axon, which has an area of 10,000-25,000 nm, so the nanorobot can be relatively large (the standard 1,000 nm is not a problem), and have a variety of functions. Synaptobots correspond to synapses which is the specialized contact area between the nerve endings of neurons. Synaptobots may be embedded in the pre-synaptic terminals at the end of the axons of the outbound signal, the post-synaptic terminals at the end of the dendrites of the receiving signal, or in the synaptic cleft. Synaptobots would need to be much smaller than axonal endoneurobots. The synaptic terminals are 100-1,000 nm^3 and the synaptic cleft is 20 nm, so synaptobots would need to be of an estimated size of 5-300 nm, with limited functionality. Such synaptobots would be delivered to synapses in a phased implementation, for example in a series of 117 shipments (Martins et al., 2019, 12). The glial cells that surround the neurons are about the same size as neurons (15,000-30,000 nm), suggesting that the gliabot could also be fairly large (1,000 nm) and support a variety of functions.

Neural Cells	**Function**	**Neuronanorobot**	**Number of Nanorobots**	
Neurons				
Axon beginning (soma (cell body))	Send signal	Axonal endoneurobot	1/neuron	86 billion
Axon ending (pre-synaptic terminal)	Send signal	Synaptobot	2300/neuron	200 trillion (86 billion x 2300)
Dendrite (post-synaptic terminal)	Receive signal	Synaptobot		
Glial cells	Facilitate signal	Gliabot	1/neuron	86 billion

Figure 6. Neural Cells and Neuronanorobot Complement.

14.2.2.1 Neural Signaling: Electrical and Chemical Process

The sophistication of the neuron in converting electrical and chemical signals is notable. Similar to global telecommunications networks that convert between electrical and optical signals for efficient transmission, so too the neuron converts signals between the electrical and chemical regime for efficient transfer (Figure 7). A neuron receives signals via dendrite and soma (for example from visual or motor stimulus), and sends them as an electrical action potential down the axon. The action potential is converted from an electrical to chemical signal in the pre-synaptic terminal and crosses the synaptic cleft as a chemical signal. In the post-synaptic terminal of the dendrites, the chemical signal is processed. The general form of neural signaling is through chemical synapses as described, but exclusively electrical synapses are used in high-stakes rapid-signaling applications such as in the heart and escape reflexes.

	Neural Signaling Step	**Signal Type (Electrical or Chemical)**	
1	Axon produces action potential	Electrical pulse	E
2	Axon ending: Action potential received at pre-synaptic terminal	Electrical to chemical neurotransmitter conversion	E-to-C
3	Signal transmitted across synaptic cleft (20 nm, 1 millisecond)	Neurotransmitters released into synaptic cleft	C
4	Dendrite: Signal received at post-synaptic terminal	Neurotransmitter reception	C

Figure 7. Neuronal Signaling Steps and Signal Types (E = Electrical, C=Chemical).

Although neural signaling is a complex electrical and chemical process, the initial B/CI implementation may be realized on the basis of electrical signaling alone, without involving chemically-based neurotransmitters (Martins et al., 2019, 10). This implies the deployment of only the axonal endoneurobot. The full implementation of the B/CI would include the chemical operations of neurotransmitters as well. Biomimetic principles could be employed to convert analog chemical signals to digital electrical signals for more efficient transfer. For example, optogenetic therapies bypass expensive rod-and-cone retinal processing by transmitting already-converted electrical signals (Williams, 2017). Neuronanorobots, their neural cell complements, and electrical and chemical signaling functions are outlined in Figure 8.

Neuronanorobot	Neural Complement	Electrical	Chemical	Function
Axonal endoneurobot	Axon	Action potential	N/A	Send action potential
Synaptobot				
Axon ending: pre-synaptic terminal	Pre-synaptic terminal	Action potential	Neurotransmitter	Electrical-to-neurotransmitter conversion
Synaptic cleft	Synaptic cleft	N/A	Neurotransmitter	Transmit neurotransmitters
Dendrite: post-synaptic terminal	Post-synaptic terminal	N/A	Neurotransmitter	Neurotransmitter-to-electrical conversion
Gliabot	Glial cell	N/A	Neurotransmitter	Facilitate neurotransmitter operations

Figure 8. Neuronanorobots and required Electrical and Chemical Transmission Functionality.

The axonal endoneurobot registers the electrical activity of the axon sending an action potential. The synaptobot in the pre-synaptic terminal can perhaps register electrical activity on the basis of the calcium emptied into the terminal as the action potential's arrival causes the voltage-gated calcium channels in the terminal wall to open. Synaptobots located in the synaptic cleft and post-synaptic terminal would need to register chemical neurotransmitter activity. Glial cells have resting potential, but operate primarily with neurotransmitters and would also need to register chemical neurotransmitter activity.

14.2.3 Neurocurrencies

A *neurocurrency* is a resource used to execute a neural function, either by a neural cell or a neuronanorobot. Each neuronanorobot may conduct a variety of autonomous or semi-autonomous activities that require the monitoring and use of resources. Such activities could be instantiated as transactions with resource balances which can be exchanged in an economic system such as a blockchain. Each activity is a transaction in which resources may be impacted. Transactions could include a small service charge (1 percent of transaction value is standard) to support the system cost of the B/CI network and to encourage cost-based resource use. Various neurocurrencies and their relevance to neuronanorobots are listed in Figure 9.

Neurocurrencies ($NC)		Neuronanorobot Species		
Category	**Resource**	**Axonal Endoneurobot**	**Synaptobot**	**Gliabot**
Electricity	Voltage	X	X	
	Polarization	X		
	Action Potential	X		
	Resting Potential			X
Ions	Sodium (Na^+)	X		
	Potassium (K^+)	X		
	Calcium (Ca^{2+})		X	
	Chloride (Cl^-)		X	
Neurotransmitters (Nx)	Glutamate (excitatory)		X	X
	GABA (inhibitory)		X	X
Fuel	Glucose (ATP)	X	X	X
	Oxygen (ATP)	X	X	X

Figure 9. Neurocurrencies by Neuronanorobot Species.

The B/CI is a multi-currency environment which could be denominated in various neurocurrencies as the coordination mechanism in the blockchain economic system. Some of the different categories of neurocurrencies might include electricity, ions, neurotransmitters, and fuel. Neurocurrency categories are generic wrappers for the different classes of resources transmitted in the neural signaling process and other operations, for example neurotransmitters is a generic wrapper for the 200 different kinds of neurotransmitters that might be exchanged.

14.2.3.1 Electricity and Ions

The primary neurocurrency is electricity. The electrical balance may be interpreted as voltage, polarization, action potential, and resting potential. A related neurocurrency by which neural operations traffic is ions (atoms stripped of one electron). The most important neural cell ion balances are related to Sodium (Na^+), Potassium (K^+), Calcium (Ca^{2+}), and Chloride (Cl^-). Ion balances may be registered as positively-charged ions (cations) or negatively-charged ions (anions). Ions are technically a form of electrical neurocurrency given their charge determinations, but are functionally distinct enough to comprise a standalone neurocurrency. Each neuron maintains a voltage gradient across its membrane due to metabolically-driven differences in sodium, potassium, chloride, and calcium ions that should be measured separately.

14.2.3.2 Neurotransmitters

The third important neurocurrency is neurotransmitters, chemical messengers of which there are over 200 in total. Glutamate and GABA are the two most common neurotransmitters in the brain (comprising 90 percent of activity), and correspond respectively to excitatory and inhibitory action. The third most notable neurotransmitter in neural signaling is acetylcholine (which increases the probability of pre-synaptic neurotransmitter release).

One canonical means of classifying neurotransmitters is by large amino acids versus small molecules (Figure 10). There are only a few large amino acid neurotransmitters, for example glutamate and aspartate (excitatory), and GABA and glycine (inhibitory). There are many small molecule neurotransmitters such as acetylcholine, dopamine, norepinephrine, histamine, serotonin, and epinephrine. Small molecule neurotransmitters may have both excitatory and inhibitory action, or just one. Marquis neurotransmitters acetylcholine and serotonin can have either excitatory or inhibitory action since they are related to general alert systems. Others such as noradrenaline signal stress, while dopamine signals the reward system. The large amino acid neurotransmitters are implicated in synapse activity, and therefore also in synaptobots. The small molecule neurotransmitters are suggested more for gliabot activity.

Neurotransmitter Class		**Stimulation**		**Neuronanorobot**	
Type	**Neurotransmitter**	**Excitatory**	**Inhibitory**	**Synaptobot**	**Gliabot**
Large amino acids	Glutamate	X		X	X
	Aspartate	X		X	X
	GABA		X	X	X
	Glycine		X	X	X
Small molecule (monoamine)	Acetylcholine	X	X		X
	Serotonin	X	X		X
	Noradrenaline		X		X
	Dopamine	X			X

Figure 10. Neurotransmitter Classes and Neuronanorobot Correspondence.

Another canonical means of classifying neurotransmitters is whether they are either ionotropic or metabotropic. Both operate by binding to transmembrane-based receptors on the receiving neuron. Ionotropic neurotransmitters cause an ion channel to open in the receiving membrane, and the less powerful metabotropic neurotransmitters trigger a signaling cascade within the receiving cells (by coupling to G-proteins). Large amino acid and small molecule neurotransmitters may be either ionotropic or metabotropic. For B/CI implementation, ionotropic neurotransmitters are more important functionally and more straightforward to model first as they lack the complicated G-protein coupled signaling cascade within the receiving dendrite.

14.2.3.3 Fuel

Fourth, but not least, a fuel balance is necessary for neural cells to conduct activity, namely by producing ATP from oxygen and glucose delivered by the blood stream. ATP is the energy currency of all cells. In neurons, ATP is necessary to drive the flow of charged ions that underlie the electrical activity of signaling. About two thirds of a neuron's energy is used to produce Sodium/Potassium ATPase, an enzyme that recharges the ionic gradients of sodium and potassium after an action potential has occurred (Morris & Fillenz, 2003, 48). Synapses likewise operate as a function of ATP-based energy per mitochondria that circulate in the synaptic terminal. High cytosolic calcium in the axon terminal triggers mitochondrial calcium uptake, which, in turn, activates mitochondrial energy metabolism to produce ATP to support continuous neurotransmission. Synaptobots could track the fuel-based activity of the mitochondria. Fuel is also important to glial cells as they mop up excess glutamate and other neurotransmitters with an ATP-dependent pump. Gliabots could track and predict neurotransmitter bursts and clean-up.

A biodesign concern for neuronanorobots is an autonomous energy source, meaning the ability of nanorobots to forage locally for the fuel necessary to sustain themselves and carry out operations. Estimates suggest that the standard nanorobot (1,000 nm) could produce several tens of picowatts of power from oxygen reaching its surface in the blood plasma (Hogg & Freitas, 2009). This would provide enough power for the steady state activities of the nanorobot. If equipped with pumps and tanks for onboard oxygen storage, the nanorobot might be able to collect enough oxygen to support burst power demands two to three orders of magnitude larger.

14.3 B/CI Hardware: Quantum Computing for Brain

"Living things are made of atoms according to the laws of physics, and the laws of physics present no barrier to reducing the size of computers until bits are the size of atoms and quantum behavior holds sway" (Feynman et al., 2005; Feynman, 1985).

14.3.1 Communication and Connectivity Platforms

An overarching theme in the decades-old development of modern science and technology is the evolution in platforms used for connectivity and communication. There continue to be new and improved technologies for connecting humans to the internet cloud and to each other. Three key connectivity platforms might be noted as the personal computer, the smart phone, and potentially, the B/CI (brain/cloud interface), as shown in Figure 11. Equally important to the realization of the connectivity platform is the backend network that supports it.

Eras of Connectivity	1970-2020	2000-2020	2030-2050e

Connectivity Platform	Personal computer	Smart phone	Brain/cloud interface
Back-end Network	Computer data networks	Global fiberoptic communications networks	Quantum computing networks

Figure 11. Evolution in Connectivity Platforms.

Highlighting the difficulty of forecasting the impact of technology, IBM CEO Thomas J. Watson famously observed in 1943 that "I think there is a world market for maybe five computers" (Strohmeyer, 2008). Indeed, the market for expensive room-sized computers may have been small, but the trend that led to the personal computer and the internet has had a huge impact. What is clear is that the overall intensity of human connectivity and communication has been increasing over time, and that the platform of choice continues to miniaturize into forms that have greater portability and on-board convenience for humans.

Current estimates suggest that by 2023, two-thirds of the world will have internet connectivity and two-thirds will have mobile telephones (Cisco, 2020). In more detail, Cisco's Annual Internet Report estimates that nearly two-thirds of the global population will have internet access by 2023 (up from 51 percent in 2018). About the same amount, 70 percent of the global population, is estimated to have mobile phones by 2023 (up from 66 percent in 2018). Internet-connected devices are forecast to be more than three times the global population (3.6 networked devices per capita, up from 2.4 in 2018). The key point is the remarkable jump in internet penetration in only five years (from 51 percent of the world in 2018 to two-thirds of the world in 2023) as smart phones proliferate. This suggests that further advance in connectivity platforms (such as the B/CI) could have similar accelerated adoption, and extend the overall portion of the population that is connected to the internet.

B/CIs require leading-edge technology and lead the development of such technology. The brain is one of the most complex systems known, and the latest research for its understanding and manipulation is needed. Existing projects such as whole-brain emulation use technologies such as supercomputing to enable massively-parallelizable cortical column simulation. However, a vastly more scalable platform beyond supercomputing such as quantum computing is necessary for the next level of understanding of the complexity of the brain (Harris & Kendon, 2010, 3581). The chemical conversion processes that take place in the brain are orchestrated by quantum mechanical principles and an analogous computing environment for representing these processes is required. The benefit of quantum computers is that they can store and process information about simulated quantum systems natively, thus providing tremendous scalability (NSF, 2016, 1). To perform a quantum simulation, the Hilbert space (three or more dimensional space) of the underlying system is mapped directly onto the Hilbert space of the (logical) qubits in the quantum computer (Kendon et al., 2010, 3609).

Quantum computing is first indicated for the realization of B/CIs due to the sheer technical scalability in processing offered by a computational substrate that is congruent to the brain (the quantum mechanical chemical exchanges by which the brain operates). Second, quantum computing addresses the security sensitivity of B/CIs, per nature's slate of security features built into the quantum mechanical domain such as the no copying and no measurement principles.

14.3.2 Quantum Computing

"Quantum computing could lead to whole new regimes of bioinspired engineering at the nanoscale" (Harris & Kendon, 2010, 3581).

Quantum computing (information processing at the quantum scale of atoms ($1x10^{-9}$ m)) is an early-stage but rapidly advancing technology (Swan et al., 2020). The field is farther along than might be thought. Commercial systems (on-premises and cloud-based) are shipping from three vendors: IBM and Rigetti (controllable gate model superconductors with 19 qubits) and D-Wave Systems (less-controllable quantum annealing machines with 2048 qubits). Advances in superconducting materials have allowed the production of superconducting chips that do not need to be cooled with bulky cryogenic equipment. Quantum computing is implicated in eventually being able to break existing cryptographic standards (2048-bit RSA), as a "Y2K for Crypto." A 2019 U.S. National Academies of Sciences report estimates that this is unlikely within 10 years (Grumbling & Horowitz, 2019), however methods are constantly improving. The U.S. NIST is developing next-generation standards based on lattice cryptography (complex 3D arrangements of atoms), as opposed to the difficulty of factoring large numbers (currently by RSA 2048), a mathematical shift to group theory (lattices) from number theory (factoring).

Quantum computing delivers an improved capacity to manipulate 3D reality at the atomic scale, which could make B/CIs more of a realizable possibility in the near-term. As a broad heuristic, quantum computing may allow a one-tier increase in the computational complexity schema (the computational resources required to compute a given problem). For example, in the canonical Traveling Salesperson Problem, it may be possible to check twice as many cities in half the time using a quantum computer. A problem that requires exponential time in classical systems (i.e. too long for practical results) may take polynomial time in quantum systems (a reasonable amount of time). The improved performance of quantum computing is due to the SEI properties (superposition, entanglement, and interference) of quantum objects. In particular, superposition allows a speed-up in processing because all problem inputs can be calculated simultaneously. All permutations of 0/1 in 3D space can be tested at the same time, until collapsed into one final answer (0 or 1) at the end of the computation.

14.3.2.1 Quantum Photonic Networks: Superposition of Superposition

The standard one-tier speed-up in computational complexity in quantum computing is due to the massive parallelism of being able to process all problem inputs simultaneously (all permutations of 0/1 in 3D space). Superposition essentially means "try all possibilities simultaneously." Optical quantum computing offers an additional tier of computational speed-up. This is because in quantum photonics, there can be a superposition of both problem inputs and processing gates ("a superposition of superposition") (Procopio et al., 2015). The difference between standard quantum computing and optical quantum computing is due to the treatment of gate architecture. Standard quantum architecture has a fixed gate order (a fixed order of logic gates through which the computation proceeds). Photonic quantum architecture, however, can have a superimposed gate order (that tests all possible permutations of gate order during the computation). In quantum photonics, there is a superposition of both form and content (gates and inputs), whereas in standard quantum computing, there is only a superposition of content (inputs). The result is that optical quantum circuits may offer an exponential advantage over classical algorithms and a linear advantage over standard quantum algorithms.

Quantum photonics might deliver greater computational capability, and also next-generation global telecommunications networks. Optical networking is at the center of global communications networks today, and quantum photonics is implicated as an upgrade technology. Although there are many ways to make qubits (quantum information bits) for quantum computing on standalone machines, for a larger architecture of networked machines, electrical signals must be converted to optical signals. Hence, there are two methods in development for quantum computing networks. One way is to create an all-optical platform from the beginning with continuous qubit optical interfaces (Sapra et al., 2020). The other method is to make a microwave superconducting platform (in the model of semiconductors) that is later interfaced to optical networks with electrical-optical interconnects.

Quantum photonics is further indicated in the construction of the quantum internet. The quantum internet is a next-generation internet proposal that would feature secure end-to-end communication as an improvement to the lack of privacy and security of the current internet. The quantum internet would employ quantum switches and routers, quantum key distribution, quantum processors, and quantum memory. One possible roadmap for migrating to the quantum internet is set forth by Wehner et al. (2018, 4). If quantum photonic networks were to become the secure global platform of choice for computing and connectivity, whole new classes of Kardashev-plus applications might become possible such as the realization of the B/CI.

14.3.2.2 Quantum Computing Neuroscience and B/CI Applications

So far, the demonstrated applications of quantum computing are in the areas of optimization and simulation. Optimization and simulation could have an important impact on the potential realization of B/CIs, whole-brain emulation, and computational neuroscience. In classical computing, state-of-the art progress includes a proposed brain-machine interface platform with 3,072 electrode-based channels (Musk et al., 2019), and a partial brain simulation of 80,000 neurons and 0.3 billion synapses, as a sample representation of the 86 billion neurons and 200 trillion synapses in the brain (van Albada et al., 2018).

Quantum computing has a great deal to offer to the complexities of neuroscience. For example, the "test all permutations" functionality of superposition could enable a more tractable approach to brain-related calculations. In the standard compartmental model of neural signaling, a single neuron might have a thousand separate compartments whose behavior might be described by tens of thousands of differential equations. The differential equations represent the numerical integration of thousands of non-linear time steps, and summarize the activity of counting the voltage spikes (threshold signals) that emanate from the neuron. This kind of modeling project becomes much more feasible with quantum computing. A deployment of this idea is proposed for modeling the pyramidal cell (one of the most sophisticated neurons) in a dendritic tree model abstracted into a two-layer neural network (Poirazi et al., 2003).

Neural signaling is often analyzed with the Hodgkin-Huxley model[4] that describes the conduction of the electrical impulse through the axon. The Hodgkin-Huxley model has been studied in the quantum regime with a hardware model that incorporates the three ion channels of the axon (potassium, sodium, and chloride), together with a signal source and output, using a system of memristors, resistors, and capacitors (Gonzalez-Raya et al., 2020). The work provides a blueprint for constructing quantum neuron networks with quantum state inputs. This could facilitate B/CI realization via quantum computing and more generally, hardware-based neuromorphic quantum computing (large-scale systems that mimic the neuro-biological architectures of the human nervous system in a computing environment (Monroe, 2014)).

[4] 1963 Nobel Prize in Physiology or Medicine per describing the propagation of electric signals in squid axons.

14.3.3 Nature's Built-in Quantum Security Features

The previous section discusses ways in which quantum computing offers new levels of computational capability and may enable a variety of projects including the realization of the B/CI. This section discusses security features specific to quantum computing (Swan, 2020). Five specific security features inherent to quantum mechanical domains are as follows. These are the no-cloning theorem, the no-measurement principle, quantum error correction through particle entanglement, quantum statistics (provable randomness), and computational verification owing to the BQP computational complexity class of quantum information (Figure 12).

	Principle	Quantum Security Feature
1	No-cloning theorem	Cannot copy quantum information
2	No-measurement principle	Cannot measure quantum information without damaging it (eavesdropping is immediately detectable)
3	Quantum error correction	Error correction via ancilla (larger state of entangled qubits)
4	Quantum statistics	Provable randomness: distributions could only be quantum-generated
5	BQP/QSZK computational complexity and computational verification	Quantum information domains compute quickly enough to perform their own computational verification (zero-knowledge proofs)

Figure 12. Natural Security Features built into Quantum Mechanical Domains.

First is the no-cloning theorem which states that quantum information cannot be copied, meaning that there is fidelity and uniqueness in any information transfer. Second is the no-measurement principle which is that quantum information cannot be viewed or measured without changing or damaging it, meaning that eavesdropping is immediately detectable (and would practically trigger a resending of the quantum information in a slightly different encoding). Third is the fact that entangled particles allow the realization of quantum error correction schemes.

Fourth is quantum statistics in that distribution signatures could have only been quantum-generated. Certain quantum statistical distributions based on the SEI properties of quantum objects (superposition, entanglement, and interference (amplitude)), have specific wave motion that could only have been generated by quantum systems and thus convey provable randomness.

Fifth is the computational complexity class of quantum information (BQP/QSZK). The computational complexity class of problems that can be solved with a quantum computer is known as BQP (bounded-probability quantum polynomial), which is contained within the computational complexity class QSZK (quantum statistical zero knowledge). Zero knowledge refers to a mathematical soundness attribute in which it is not necessary to have any knowledge of an underlying process (i.e. zero knowledge), only the result. Quantum computers operate quickly enough to perform their own computational verification (zero-knowledge proofs) of the results as part of their operation. Together, these native security features of quantum information domains suggest that quantum computing confers an extremely secure processing environment.

14.4 B/CI Software: Holographic Control Theory

The previous section elaborates quantum computing as the hardware platform for the B/CI and the next sections discuss the control software and the operating software. For the control software, a holographic control theory (based on the AdS/CFT correspondence) is proposed as a control theory to bridge the macroscale and quantum domains (B/CI computations are carried out in a cloud-based quantum computing environment). B/CI neuronanorobot network data is collected and computed in the quantum mechanical form and abstracted for practical use by human administrators at the macroscale. For the operating software, a blockchain-based neuroeconomic system is proposed to coordinate the in-brain B/CI neuronanorobot network.

14.4.1 Holographic Correspondence (the AdS/CFT Correspondence)

Considering software for the B/CI quantum computing cloud platform, a logical choice is a holographic control theory based on the AdS/CFT correspondence. Quantum reality (most especially in this case, the brain and the B/CI) is a domain of quantum information processing, and hence an information-related control theory makes sense. The AdS/CFT correspondence is a known model for linking the quantum and macroscale domains. The AdS/CFT correspondence (also called holographic correspondence, gauge-gravity duality, and the bulk-boundary relation) is the claim that in any physical system, there is a correspondence between a volume of space and its boundary region such that the interior bulk region can be described by a boundary theory in one fewer dimensions. The AdS/CFT correspondence is a formalization of the holographic principle which denotes the possibility of a 3D volume being reconstructed on a 2D surface.

14.4.1.1 AdS/CFT Correspondence (Anti-de Sitter Space/Conformal Field Theory)

The central idea of the correspondence is that a messy bulk process running in a 3D volume can be written in a simplified manner as a surface theory on the boundary in one fewer dimensions. The AdS/CFT correspondence is analogized to a soup can, in that the bulk is the 3D interior of the can and the boundary is the 2D exterior label of the can. This is a useful visual representation of the difference between a 2D surface and a 3D bulk. However, more technically, AdS is referring to anti-de Sitter space as opposed to regular de Sitter space. Regular de Sitter space is the normal 3D space of lived reality, which can be described by Euclidean geometry. Anti-de Sitter space is a simplified model based on the hyperbolic geometry of a sphere, and looks like the *Circle Limits* works of Escher that have pictures of fish and bats getting smaller and smaller as they extend towards the edge of a circle. Anti-de Sitter space is used in physics as a solvable model of de Sitter space. The benefit of the AdS/CFT correspondence is that a complicated bulk region can be solved analytically and related to a boundary region in one fewer dimensions. CFT is conformal field theory which means any basic (conforming) field theory.

14.4.1.2 Solve Messy Bulk System and Elicit Emergent Structure

Applying the AdS/CFT correspondence renders what seems to be an intractable bulk volume in a manner that is solvable as a boundary theory in one fewer dimensions. For example, the overall universe could be considered as a bulk volume for which there might be a boundary theory that describes it, in one fewer dimensions. Even without accessing the edge (getting outside of the universe), the correspondence is a formal model that might be applied to derive information about the emergence of bulk structure such the distribution of matter, and the development of space and time. Not only can a messy bulk volume be solved for practical use in one fewer dimensions as a surface theory, but also emergent structure might be elicited to study the parameters of system. For example, in many complex systems, the endpoint is known (e.g. GDP), but not the patterns that arise along the way (e.g. merchant-consumer interactions) to define the result. The correspondence can be used as a technology to study complex systems.

Some examples of complex systems with emergent structure are food web ecosystems, financial risk, social networks, and machine learning networks. In systemic financial risk, the process of contagion that leads to collapse is unknown. How influencers build traction in social networks is likewise a target of study. Machine learning is a black box in which it is unclear how the backpropagation and feed-forward network operations cycle to produce an optimal classification algorithm. Similarly, biological processes in the brain, and maybe B/CI operations, are black box systems that might be studied with the correspondence as a complexity technology.

14.4.2 The Black Hole Information Paradox

The AdS/CFT correspondence was proposed by Maldacena (1997) as a formalization of the Holographic Correspondence developed by Susskind (1995) as a resolution to the black hole information paradox. The black hole information paradox asks how it is possible for information to exit from a black hole. The conundrum arises from trying to understand Quantum Mechanics and General Relativity together. The paradox is that on the one hand, information apparently cannot escape from black holes (per General Relativity), but on the other hand, Hawking radiation does emanate from black holes. The only way that information (quantum information bits) can be in the Hawking radiation is if what is inside the black hole is copied, but the no-cloning theorem prevents quantum information from being copied (per Quantum Mechanics).

Susskind proposes the holographic principle (also called black hole complementarity) to resolve the black hole information paradox. The premise is that there are complementary views, both accurate, of the same physical phenomenon in the universe. This is not a stretch as various time paradoxes (e.g. grandfather and twin) have been demonstrated in General Relativity, that phenomena look different to different observers in the universe due to time dilation. In the case of the black hole information paradox, the far-off observer sees information smearing out on the event horizon surface of the black hole in 2D, but not actually entering the black hole. On the other hand, the near-by observer that is jumping into the black hole sees information in 3D, entering the 3D interior volume of the black hole. The complementary views suggest that there is no conflict, thereby resolving the paradox. The boundary (black hole event horizon) is described by a 2D surface theory, and the bulk (black hole interior volume) is described by a 3D volume theory. The cornerstone principle of the AdS/CFT correspondence is nicely demonstrated as a surface theory describing a messy bulk process in one fewer dimensions.

14.4.2.1 The AdS/CFT Correspondence as Gauge-Gravity Duality

Continuing to solve puzzles between General Relativity and Quantum Mechanics, Maldacena further instantiates the AdS/CFT correspondence as Gauge-Gravity Duality (2012). Gauge-gravity duality relates gravitational fields (General Relativity) and gauge theory fields (Quantum Mechanics). The intuition is that both gravity and gauge theory are field-based phenomena at the scale of gauge theory (1×10^{-15} m), and therefore might be joined through the correspondence. Whereas quantum mechanics (1×10^{-9} m) describes the behavior of atoms, gauge theory describes the behavior of subatomic particles (such as gluons and quarks) that comprise atoms. At the scale of gauge theory, fields of flux may describe how force particles (bosons (gluons)) hold sub-atomic matter particles (fermions (quarks)) in place in atomic configurations. The AdS/CFT correspondence as gauge-gravity duality is an example of a foundational physics advance that may inform the understanding of the brain and the implementation of the B/CI. Whereas brain activity is often considered at the scale of the quantum mechanical interactions of neurons (1×10^{-9} m), the subatomic particle scale of gauge theory (1×10^{-15} m) might illuminate the next level of the sub-cellular processing of synapses.

14.4.2.2 AdS/BCI: Bio-correspondence, Holographic Synapses, Neuronal Gauge Theory

This section more robustly proposes the idea of a neuronal gauge theory and its relation to the AdS/CFT correspondence. Whereas neural cells are 10,000-25,000 nm and glial cells are 15,000-30,000 nm, the synaptic terminal area is only 100-1,000 nm^3 in size, and the synaptic cleft is a mere 20 nm (Appendix). Brain function thus takes place at two different scale levels, neuronal activity at the atomic scale (1×10^{-9} m) and synaptic activity at the subatomic particle scale (1×10^{-15} m). Hence, different physical theories are implicated to explain and manipulate the brain at the two relevant scale levels.

Theories at the subatomic particle scale are referred to as quantum field theories or gauge theories. In particular, the *gauge* in gauge theory implies invariance in the system per the change of certain properties, mathematical transformations that can be applied, and the existence of symmetries. Applying physical theories to the study of the brain is a natural inclination, and one such neuronal gauge theory has been proposed (Sengupta et al., 2016). This theory, however, is primarily based on the principle of an organism's capability to minimize free energy.

What is needed is a neuronal gauge theory that engages the features, manipulations, and formalisms of existing quantum field theories in a biophysics interpretation. Quantum *field* theories indicate that particles and forces arise as vibrations of fields as a more fundamental level of organization. The biophysics applications of quantum field theories may not be straightforward as even the most basic physical principles can be different in the biophysics context. For example, the shortest distance in biophysics may not be a straight line as pressure gradients and other factors propel materials in diverse ways. This is even before considering sophisticated biophysical mechanisms such as the Nernst potential and diffusion dynamics.

The idea is to explore an interpretation of recent advance in quantum field theories to develop a robust suite of neuronal gauge theories. In particular, this could be through the application of MERA, SYK, and tensor network models to study the high dimensional aspects of quantum-many body systems (Gurau, 2016), instantiated in a quantum machine learning environment (Carrasquilla, 2020). An interpretation of quantum physics advance in the context of the brain is non-trivial given the domain-specific concerns of biophysics.

Moreover, it may be possible to define a Bio-correspondence or Holographic Synaptic theory as a biophysical interpretation of the AdS/CFT correspondence. The correspondence is emerging as a workhorse theory for describing systems in one dimension less from a surface theory. The correspondence could have an interpretation in the neuron-synapse system in which the neuron is the surface dual to the messy bulk volume the chemical signaling in the synapse.

14.4.3 The AdS/CFT Correspondence as a B/CI Control Theory

The AdS/CFT correspondence can be used as a control theory for a variety of systems, including those that span the macroscale and the quantum domain. More generally, the correspondence is an example of a two-tier information system. There are many two-tier systems which have complex operating processes that must run in real-time in the physical bulk to produce a final answer of interest in one fewer dimensions in the boundary (Figure 13). More formally, these systems can be described as one-way functions (Goldreich & Levin, 1989).

	Messy Bulk Process	Boundary Output
1	Air particles moving in a room	Temperature
2	Merchant-consumer interactions	GDP
3	Quantum mechanical reality: particles jiggling	Macroscale reality: table
4	Information entering black hole interior in 3D	Information smeared out on event horizon in 2D

5	Ancilla of larger entangled state	Error-corrected qubit
6	Hash function algorithm	Hash code output
7	Zero-knowledge proof	T/F value
8	Proof-of-work mining	Confirmed transaction block
9	Holographic annealing	Lowest energy state of a system
10	Protein folding process	Folded protein
11	Speculative exchange of oil (8-15x/barrel)	Consumed resource

Figure 13. Two-tier Information Systems with Bulk-Boundary Relationships.

Two-tier information systems can be instantiated in bulk-boundary relationships with the AdS/CFT correspondence. Moreover, the AdS/CFT correspondence can be used as a control theory to manage these processes. Surface theories can be used to control bulk processes. The insight of the correspondence is that any fleet-many unit domain can be orchestrated using the correspondence as a control theory. As a control theory, the correspondence brings "particle-many domains" under management with a temperature term. The AdS/CFT correspondence is a universal control theory that might likewise apply to taxis, spaceships, and B/CIs.

B/CIs require a control theory that spans the macroscale of lived reality and the quantum domain of the brain and the B/CI. The correspondence is an excellent candidate for such a B/CI Control Theory. B/CIs have fleet-many items that need to be managed. The fleet-many units are the on-board neuronanorobots embedded in the brain which comprise the B/CI network. The B/CI domain is quantum mechanical, both in its physical reality in neuronanorobot operation, and in its computational instantiation for control via the quantum computing cloud environment. The AdS/CFT correspondence easily spans the quantum scale and the macroscale and provides a surface-level theory for controlling messy processes in the quantum mechanical bulk.

14.4.4 The AdS/CFT Correspondence as a Control Model for Complex Domains

The AdS/CFT correspondence is a universal control theory, and especially, a control theory for complex domains. Complex adaptive systems are those that are non-linear, emergent, open, unknowable at the outset, interdependent, and self-organizing. In the B/CI context, two aspects of complexity management are of interest, identifying novel structural emergence, and providing an ambient control structure.

Identifying novel structural emergence is a key property of the AdS/CFT correspondence. The correspondence was initially developed to understand more about how the physical structure of the universe evolved, structure such as matter, geometry, and space and time. Structural emergence is the target of AdS/ML (machine learning) research to understand how the black box of deep learning systems settle upon certain algorithmic structures as being optimal. In the B/CI, one of the most important structural emergences is new ideas. Novelty in the form of ideation is a crucial outcome for B/CI cloudminds, whether individual or collective. Mechanisms for identifying new ideas as emergent structure via the holographic control theory could be essential for B/CI implementation. Positive emergent structure in B/CIs is new ideas. Negative emergent structure is useful too, to signal problems developing in the B/CI as a complex adaptive system. Known aberrant behavioral patterns that emerge in automated fleets may likewise have an analog in B/CI networks. For example, in Unmanned Aerial Vehicle (UAV) networks, thrashing, resource-starving, and phase change have arisen (Singh et al., 2017), and in deep learning, vanishing gradients (disappearing problem horizons) is a known problem (LeCun et al., 2015).

Providing an ambient control structure is a second attribute of the correspondence-based control theory. The scope of operation of complex systems is by definition unknown at the outset and thus requires a flexible control model that evolves with the system. B/CIs need a control model, but it is too early to know exactly the detailed requirements of such a control system. Therefore, it makes sense to select a flexible control model that may be able to handle any variety of potential situations that arise. Even the basics of B/CI operation are as yet unknown, such as the suite of on-board versus remote control features. Likewise, energy requirements and local resource availability are unknown. The "temperature terms" that are most relevant for the B/CI are unclear. Further, even once identifying relevant temperature terms, the corresponding "thermostat" for their control is needed. Hence, the AdS/CFT correspondence is indicated as a flexible control model for the complexity of the B/CI and its operating environment.

14.4.5 AdS/CFT Correspondence Studies

The AdS/CFT correspondence is a universal control theory that not only orchestrates macroscale-quantum domains, but also complex systems. Given its management of messy bulk processes from a simplified boundary theory in one fewer dimensions, the correspondence is proving to be a foundational model with application in many fields. Beyond cosmology and physics, some of the other disciplines employing the correspondence include materials science (strongly-coupled domains such as superconductors, condensed matter, and plasma physics), machine learning, network theory, and blockchain distributed ledgers (Figure 14).

AdS/CFT Correspondence Variation		Application Functionality	Reference(s)
AdS/CFT	AdS/Conformal Field Theory	Cosmology, particle physics	Maldacena, 1998
AdS/CMT	AdS/Conformal Materials Theory	Strongly coupled systems: condensed matter, superconductors, plasma physics	Sergio & Pires, 2014; Hartnoll et al., 2018
AdS/ML	AdS/Machine Learning	Elicit bulk structure with deep learning networks; rewrite Ryu-Takayanagi bulk-boundary entropy with maxflow–mincut	Hashimoto et al., 2018; Freedman & Headrick, 2017
AdS/DLT	AdS/Distributed Ledger Technology	Holographic consensus, quantum smart routing, certified randomness	Kalinin & Berloff, 2018
AdS/B/CI	AdS/Brain/Cloud Interface	Holographic backup, ad-hoc field assembly, and neurocurrency transfer	Swan et al., 2020

Figure 14. AdS/CFT Correspondence Studies.

14.5 B/CI Operating Software: Bio-blockchain Neuroeconomy

The last section elaborates a holographic control theory for the B/CI as a control lever between the macroscale of everyday physical reality and the quantum mechanical scale of the quantum computing platform. The holographic control theory coordinates between the B/CI neuronanorobot network (with data collected and computed in the quantum mechanical form) and its abstraction for practical use by human administrators at the macroscale. What is still required is to articulate an operating software for the B/CI neuronanorobot network itself, to describe how the fleets of particle-many neuronanorobots are to be orchestrated to perform their in-brain activities, and for this, a blockchain is proposed. A blockchain is an automated cryptographic system for value transfer and secure transaction logging (Swan, 2015a). The holographic control theory can be implemented as a blockchain-based economic system. The correspondence is a control theory, a model for controlling a system, and the system to be controlled is the network of neuronanorobots embedded in the brain that comprise the B/CI.

14.5.1 Bio-blockchain Neuroeconomy

Economic concepts are the design principles of the B/CI network operating software. The B/CI neuronanorobot network could use a bio-blockchain (a blockchain deployed in a biological setting) as a transaction-logging system for the neuronanorobots who have pre-programmed goal-directed behavior and carry out neurocurrency-based operations. A blockchain is implicated for the B/CI operating software for technical feasibility and for security reasons. From a technical perspective, a modern smart network technology is needed that is transaction-heavy, network-based, and automated. The B/CI must orchestrate particle-many fleet units and their activity. A blockchain is able to seamlessly register an arbitrarily-large number of participants and likewise may be able to execute an arbitrarily-large number of transactions. Thus, a bio-blockchain economic system is a top choice for operating software for an automated transaction system. Blockchains support a multi-currency environment, in the case of the B/CI, neurocurrencies such as electricity, ions, neurotransmitters, and fuel as the basis for the execution of operations. Security (and trust) is created by the cryotographic features inherent to blockchains such as real-time transaction confirmation. Finally, blockchains are a modular system that can easily scale in B/CI cloudmind implementation from individuals to groups. The same transaction-logging and security features are relevant to group cloudminds for intellectual property tracking, credit assignment, and privacy protection as for individual cloudminds.

14.5.2 Tech Specs: B/CI Neuronanorobot Network System Requirements

The first operation of the B/CI is instantiating neural signaling in a computational system. To do so, the technical requirements are for a B/CI transaction system that instantiates particle-many fleet units (neuronanorobots) and their activity. This is on the order of 86 billion axonal endoneurobots, 86 billion gliabots, 200 trillion synaptobots, and their activity, which may exceed one transaction per second per unit (Figure 15). B/CI Phase I implementation is estimated to only include electrical signaling, as action potential impulse tracking with axonal endoneurobots. B/CI Phase II implementation would include the full inventory of addressable entities (also the 200 trillion synaptobots and 86 billion gliabots), engaged in electrical and chemical signaling processes that are both cellular and sub-cellular (synaptic processing). Initial B/CI deployment would likely focus on a specific brain region, function, or activity, with whole-brain to follow.

Neuronanorobot Class	Number of Neuronanorobots	Number of Transactions (total)
Axonal endoneurobot	86 billion	1 per/second or more x 86 billion
Synaptobot	86 billion x 2300 = 200 trillion	1 per/second or more x 200 trillion
Gliabot	86 billion	1 per/second or more x 86 billion

Figure 15. Neuronanorobot Transactions.

The data processing requirements entail enabling a B/CI to have controlled connectivity between the neural activity of neurons and synapses and external data storage and processing. B/CI neuronanorobots would need to have an extremely fast wireless transmission capability, on the order of 6 x 10^{16} bits per second (Martins et al., 2019, 1). The idea is to transmit synaptically-processed and encoded human-brain electrical information via auxiliary nanorobotic fiber optics (30 cm^3) with the capacity to handle up to 10^{18} bits/second and provide rapid data transfer to a cloud-based computing environment for real-time brain-state monitoring and data extraction.

14.5.2.1 B/CI Neuronanorobot Network Traffic

Figure 16 outlines B/CI applications by traffic type with the relevant neurocurrency ledger units in which the transactions might be denominated, tracked, and exchanged. Existing applications offered by the core BCI include neuroprosthetics and computer cursor control. These activities are electrical transactions tracked with EEG signals as the type of traffic that is being transmitted, and are denominated in microvolts. The application classes for the cloudmind B/CI are mapping the connectome, monitoring on-going neural activity, curing and preventing disease, and enhancing neural performance in learning, productivity, and experiential enjoyment.

Application Class	Application	Functionality	Traffic Type	Ledger Unit
Core BCI				
Current applications	Neuroprosthetics	Actuation	Electricity: EEG signal	Microvolts
	Cursor control	Actuation	Electricity: EEG signal	Microvolts
Cloudmind B/CI				
Map	Connectome	Functional mapping	IP: 3D point cloud (SLAM)	MB, spatial placement
Monitor	Data upload, backup	Security, privacy	IP: HTTP POST/GET	MB, SLAs
Cure	Intervention delivery, Preventive maintenance	Disease cure, rejuvenation	Electricity: ultrasound; Pharmaceuticals, Cellular therapies	Millivolts (mV), Millimoles (mM), Cells
Enhance	Transparent shadowing, Direct neural transfer	Stimulaton, augmentation	IP: HTTP POST/GET	MB

Figure 16. B/CI Applications by Traffic Type and Neurocurrency Ledger Units.

As a communications platform, the B/CI network must accomodate different kinds of traffic. At minimum, this could include IP traffic (Internet Protocol), electrical signaling, and neurotransmitters. Just as the internet transfers different kinds of traffic with different software protocols (e.g. data, voice, and video traffic), so too the B/CI network will need to transfer different kinds of traffic related to its activities. Each traffic type could have its own software transfer protocol (i.e. operating instructions), neurocurrency, and measurement metric. Electricity is one neurocurrency, denominated in millivolts (mV), that allows the transfer of signals and the provisioning of field potentials. Another neurocurrency is neurotransmitters (e.g. serotonin, dopamine, and GABA), measured in nanomolar concentrations denominated in millimoles (mM). Internet traffic could be mainly in the form of HTTP POST/GET requests for posting status and retrieving information, measured in MB of data transferred along with the data transfer rate and SLAs (service level agreements). Connectome mapping has a specialized form of traffic to capture 3D positioning information about neural entities via simultaneous localization and mapping (SLAM) point clouds, and could be measured in MB of 3D data. The main traffic type and neurocurrencies applicable to the neural signaling support operations of neuronanorobots are listed in Figure 17. Different neurocurrencies may be used to transfer electrical and chemical traffic on the B/CI network.

Neuronanorobot	Traffic Type	Neurocurrency	Ledger Unit
Axonal endoneurobot	Electricity	Electricity, Ions	Millivolts (mV)
Synaptobot	Neurotransmitter	Neurotransmitter	Millimoles (mM)
Gliabot	Neurotransmitter	Neurotransmitter	Millimoles (mM)

Figure 17. Neuronanorobots, BioCurrencies, Traffic Types, and Neurocurrencies.

14.5.2.2 B/CI Neuronanorobot Network Communication

Neuronanorobots may communicate with the cloud, each other, and directly with neural cells (Figure 18). Interfacing with the cloud would be via IP traffic. Communicating with other neuronanorobots in the B/CI network would be via IP traffic and neurocurrency balances. Interacting directly with neural cells would be via native neurocurrencies (electricity, ions, neurotransmitters, and fuel). For communication between nanorobots, different models of biophysics-based chemical signaling have been proposed. For example, one nanorobot might guide other nanorobots to malignant tissues by issuing a higher intensity or gradient of E-cadherin as a chemical signal (Cavalcanti et al., 2006). For communication directly with neural cells, neuronanorobots might use a combination of electrical signaling to manage polarization, channels, and potential, and chemical signaling to mediate neurotransmitter delivery.

	Neuroanorobot Communication	Traffic Type	Task Activity
1	To the cloud (two-way)	IP (Internet Protocol)	HTTP POST/GET
2	To other neuronanorobots	IP & Neurocurrency	Messaging, resource balancing, group coordination
3	To neural cells	Neurocurrency (Electrical and Chemical)	Polarization, voltage-gating; Neurotransmitter delivery

Figure 18. Neuronanorobot Communications: Cloud, B/CI Network, and Neural Cells.

14.5.2.3 Bio-blockchain Neuroeconomy Implementation

To implement a bio-blockchain neuroeconomy, the first step is to assign each entity a unique identification number (address) so that all activities can be logged by the system. An inventory of fleet-many units is thereby created. The next step is to assign operating goals, allowed functions, and resource balances to classes of units. Just as their real-life cell complements, neuronanorobots could begin with basic neurocurrency balances (for electricity, ions, neurotransmitters, and fuel). Third, security, backup, and lifecycle management parameters could be assigned to groups of units. Finally, smart contacts (automatically executing programmatic instructions) could be instantiated for autonomous control of neuronanorobots, including the safety measure of an OFF switch in the case of gross system failure.

Three specific phases of neuronanorobot implementation can be articulated as the instantiation, operation, and exception reporting of the B/CI network (Figure 19). To begin, entities are created, resource balances assigned, and goals applied. In the operating phase, neuronanorobots perform tasks, their behavior is logged and monitored, and their lifecycle is managed in terms of instantiation and retirement, and ingress and egress to their embedded location in the brain. In the exception reporting phase, security procedures are followed and risk management is performed. Anomaly detection techniques can be applied from complexity science to identify unexpected behavior that may develop in B/CI neuronanorobot fleets.

Instantiation	Operation	Exception Reporting
•Create entities •Allocate resource balance(s) •Assign goals	•Run •Log and monitor behavior •Lifecycle management	•Security •Risk management •Anomaly detection

Figure 19. Bio-blockchain Neuroeconomy Operating Phases.

14.5.2.4 Neural Lightning Network for Neurocurrency Replenishing

Biomimetic principles could be employed in the design of a resource recovery mechanism similar to that used by glial cells. The glial cell neurotransmitter recycling operation is analogous to payment channel resource rebalancing in blockchains. In blockchain economic networks, overlays such as the Lightning Network allow parties to pre-contract to automatically rebalance accounts (analogous to airline refueling contracts or replenishing a checking account from a linked savings account if the balance dips below a certain level) (Poon & Dryja, 2016). The B/CI neuronanorobt network could likewise run a payment channel system. Neuronanorobots could contract with each other ahead of time as a feature of the blockchain-based smart contracts that orchestrate their operations anyway. The contracts could instantiate dynamic resource rebalancing, meaning the agents (neuronanorobots) would not need to transact with each other constantly and directly in real-time, but could rather participate in an automated resource rebalancing scheme (still executed as unitary transactions, but carried out automatically).

Biomimetic principles might also be used to harness the group coordination feature built into neural signaling. The B/CI network could similarly encourage and reward multi-agent behavior. For example, serotonin balances could be distributed to neuronanorobots, who link their activity towards a group goal such as improving synaptic release of serotonin in signaling, with the macroscale result of reducing depression. The practical benefit could be reducing the side effects of prescription drugs with the more granular native activation of neurotransmitters.

14.6 Peak Performance B/CI Cloudminds

The previous sections outline the hardware and software platforms for the B/CI cloudmind, and this section considers the challenges of implementing B/CI cloudminds in a group setting. Beyond the individual B/CI cloudmind (one mind connected to the internet cloud), there are issues specific to the implementation of group B/CI cloudminds (multiple minds safely connected to the internet cloud via B/CI for collaborative activity in the concept of the "the ten billion synapse world mind"). For the realization and peak performance of B/CI cloudminds, effort is needed along two implementation trajectories, one to instantiate well-formed groups, and the other to overcome hindrances specific to large-scale group collaboration.

14.6.1 Instantiating Well-formed Groups

The parameters for well-formed groups are known and could likewise apply to B/CI cloudminds. Three important aspects are as follows. A central understanding of group dynamics is conveyed by the forming-storming-norming-performing heuristic (Tuckman, 1965). This model of group development suggests that these phases are all necessary and inevitable in order for a team to grow, face challenges, find solutions to problems, plan work, and deliver results. The second aspect of well-formed groups is Simondon's group individuation principles. These principles stipulate that the group must re-form per each new participant's entry or exit, in order to vest all participants in the aims and responsibilities of the group (Swan, 2015c). The third aspect of well-formed groups is an effective governance model. One such governance model for organizing group tasks is Convergent Facilitation (Kashtan, 2014). Transparency and voluntary participation in decision making is the core principle, based on the idea that everyone wants to know how decisions are being made, but not necessarily be involved in all decisions. These three principles of forming-storming-norming-performing, group individuation, and transparent decision making could provide an empowering start to the implementation of B/CI cloudminds.

The other implementation trajectory that is also necessary for peak cloudmind performance involves addressing potential barriers to large-scale group collaboration. These hindrances can be identified as the three "Cs" of credit assignment, coordination (e.g. the sheer feasibility of how to multi-thread human capability), and communication.

14.6.2 Overcoming Barriers to Large-scale Group Collaboration

14.6.2.1 Credit Assignment

The first barrier to effective team collaboration is credit assignment. Credit assignment is the issue of the individual getting credit for contributions to the group project, and the rewards matching the contribution (both extrinsic and intrinsic rewards). For example, open-source software projects are seen as a situation of asymmetric effort and reward in that a substantial amount of value has been created, but gone largely unremunerated. The advent of blockchains helps to solve the credit assignment problem. All electronic activity is recorded, logged, and tracked, and an overlay of smart contracts (programmatic contracts) and machine learning could be applied to identify idea generation and reward such value creation. For example, via online software versioning tools and databases such as Github, the capability now exists to track any line of open-source code called in any future project. The vast corporate codebases built on open-source software could be remunerated in an annuity-type mechanism with a royalty payment every time a line of software is called. A science fiction example of the idea of automated cloud-based tracking and remuneration of intellectual property creation as a standard feature of group collaboration contracts is outlined in *Rainbow's End* (Vinge, 2007). Through blockchain-based smart contracts and other digital-tracking mechanisms, enough progress has been made towards solving the credit-assignment problem that individual minds (human and machine) might be comfortable participating in B/CI cloudminds. Blockchains provide a next-generation governance and social contracting tool for outlining the rights and responsibilities of B/CI cloudmind participation in granular detail (Swan, 2019).

14.6.2.2 Coordination

Following credit-assignment, the next potential barrier to cloudmind participation is the sheer practical feasibility of multi-threading participation into a coherent whole. As one task may have multiple threads to be knit together, so too do individual participants need to be brought together in a group endeavor. Assuming minds agree to be coordinated in a collaborative effort, how does such collaborative effort proceed? There are several existing examples of models for the effective multi-threading of participation in group projects.

Agile Programming: One premise is that small teams are most effective. At minimum the free-rider problem (uneven contribution as an unavoidable problem in team projects) is reduced and accountability is high. An extremely pared-down model of small team formation is agile software programming. Two coders are paired, one who writes code and the other who reviews and debugs it, in tight interactive cycles at the smallest unit level of productivity. Agile pair partners for specific cloudmind tasks is a possibility but does not address the issue of how to combine hundreds and thousands of human and machine minds in a greater complexity of tasks.

Cathedral versus Bazaar: Another model of software development is the Cathedral versus the Bazaar, or closed-source versus open-source (for example, Microsoft versus Linux). The Cathedral relies on in-house developers that design, code, test, and publish proprietary software in significant releases. The Bazaar is the model of developing software publicly on the internet in open-source projects with frequent releases of minor updates. Proponents of the open-source model claim that it is more efficient because bugs can be discovered more quickly with the source code being widely available for public scrutiny and testing, as opposed to the time and effort needed to find bugs in the closed model in which code is only available to a few developers (Raymond, 1999). There are benefits to both the Cathedral and the Bazaar, and B/CI cloudminds could be styled on either. Higher-risk endeavors often indicate a more hierarchical governance model (early warning signals of global financial contagion, for example) whereas creative endeavors tend to favor a flatter governance model (creative expression cloudminds).

Moon Landing: A marquis example of multi-threading diverse human capability into a coordinated endeavor is the project management virtuosity of Mission Control, created at NASA by Christopher Craft in 1969. In the mission control concept, the key point is selecting a team in which each person is an expert. The core mission control team was about 45 people, each desk in the iconic room having a specific focus (Craft, 2001). Each person was an expert and knew their particular systems more closely than anyone else. The closest expert in each area was trusted and responsibilities were clear. The team was tied together in the overall mission, that was also clear and tangible, involving human life and the "moonshot" vision. The 5-control floor Mission Control building at Johnson Space Center in Houston TX continues to bear Craft's name today. For B/CI cloudmind design, the take-away point is the division of labor. The same principle of enrolling only one expert on each specific topic could be followed likewise in cloudminds. The value of a galvanizing mission and charismatic leadership is also not to be undersold.

Polymath Project: Cloudminds already exist in the form of online collaboration communities. There are several examples, the first is open-source software development. There are also wisdom of the crowds group competition sites such as Kaggle, and R&D markets such as InnoCentive. One of the most interesting prototypes for B/CI cloudminds is the Polymath Project, an online collaboration to solve mathematical problems begun in 2009. Several problems have been solved that have resulted in publication, for example finding a combinatorial proof to the Hales-Jewett theorem (Polymath, 2012), and calculating bounds on density of Hales-Jewett numbers (Polymath, 2010). For the first problem, forty people contributed and the problem-solving effort took seven weeks. A study of the project finds that a small percentage of users created most of the content, but almost all participants contributed some content that was influential to solving the problem (Cranshaw & Kittur, 2011). The study also finds that leadership played a key role, and suggests design parameters for online collaboration communities regarding coordination, task identification, and managing background material.

14.6.2.3 Communication

Assuming that credit assignment and multi-threaded coordination is solved, the third barrier to effective group collaboration is communication. This work argues that misunderstanding can be seen as an issue of the interoperability between minds.

Communication is a function of language and meaning. Language is the minimal frontier for effective communication, as worldwide collaboration teams already know. Natural language translation is, to some basic extent, a solved problem through Google Translate (which delivers a version of the Babblefish concept (an in-ear unit that performs simultaneous translation)). The near-simultaneous translation of any electronically-capturable medium is a real-life actuality, and could be a standard feature in B/CIs. It is well-known, however, that language only construes a small portion of meaning. Communication is purportedly 7 percent verbal and 93 percent non-verbal (55 percent body language and 38 percent voice tone) (Yaffe, 2011). The problem is that language is a limited narrowband communications medium that leads to miscommunication and misunderstanding per humanity's diverse value systems, cultural backgrounds, and experiences.

With unprecedented secure access to the brain and biophysical response (parasympathetic nervous system stimulation, neurotransmitter activation, etc.), there is an opportunity for B/CI cloudminds to innovate methods of beyond-language communication. There are many examples in science fiction, first and foremost is telepathy. Another possibility is direct neural transfer, contemplated in both science (Martins et al., 2019, 15), and science fiction (Chiang, 2002, 201). Nancy Kress elaborates new concepts in group communication. One is individuals experiencing "head pain" as a signal of being out of alignment with the "shared reality" of the collective unconscious (in the *Probability Moon* trilogy 2000-02). Another idea is the holostage described in the *Beggars in Spain* trilogy (1993-96). A holostage is a medium in which a thought string is projected in the form of a hologram with all of its related associations. The viewer can see the genesis and rationale for the thought (i.e. insight into the values of the thinker), thus reducing the possibility of miscommunication. Thought string projection is described as follows.

> Speaking any single sentence to the computer, the holostage begins to form a three-dimensional shape of words, images, and symbols linked to each other. The holostage brings out the associations the mind makes, based on its store of past thought strings and algorithms for the way that mind thinks. (Kress, *Beggars and Choosers*, 1994, 17)

Instead of a single language-based sentence, a full thought is projected. B/CI cloudminds could likewise be based on a richer expression of participant thoughts, in projected holograms or other modes of wideband communication.

14.6.3 IPLD (InterPlanetary hash-Linked Data structure) for Brain

B/CI cloudminds will exist in a digital environment. This means not only that activity can be seamlessly tracked and logged (for credit-assignment and privacy protection), but also that other checks and balances can be applied such as enforcing format compatibility. No transaction can enter the B/CI system without being in a compliant format. The gain is that ideas might be brought into greater alignment from the beginning based on the way that they are presented.

The benefit of the digital format is that interoperability can be forced. SMTP (simple mail transfer protocol) forced interoperability between Compuserve and AOL, which were previously "walled garden" properties only allowing email communication among community members. Now email can be sent to any recognizable address. Contemporary challenges such as "big data is not smart data" are partially due to non-interoperable formats, for example between different electronic medical record (EMR) systems. The B/CI cloudmind could force interoperability between thoughts, thereby partially reducing misunderstanding to a formatting problem.

IPLD (InterPlanetary hash-Linked Data structure) is a general proposal for the interoperability of internet-based digital content (Benet, 2017). In the IPLD system, each content item has an address, a URL-based location where it resides in the cloud, and can be called by other programs. The web is treated as a unified information space in which all content addressed in a compatible formatting system can be called. IPLD is an overlay standard for accessing such compatibly-addressed data. A hash-linked data structure is used to protect data security and privacy, and to provide the interoperable format. This means that the URL that contains the content is not given, but rather a hash of it. A hash is a fixed-length code that corresponds to the underlying content (the URL in this case) and can only be decoded with the hashing algorithm. Hash functionality is a known technology routinely used to send data such as passwords and credit card numbers across the internet securely. In the IPLD system, a hash of the URL location of addressable-content is sent that the receiver decodes to access the content at that URL.

IPLD is essentially a file system for accessing the web's content, the vast corpora of all existing on-line content, for example Github code and Pubmed health publications. A similar content-addressing system could be used for the brain to implement both individual and group B/CI cloudminds. Just as IPLD is an overlay for the web, IPLD for Brain is an overlay for the B/CI. Instantiated in a blockchain, B/CI entities and their transactions are already in IPLD-ready formats and can automatically participate in the IPLD content-addressing system. IPLD for Brain is a specialized application of IPLD as a general data standard. In a B/CI cloudmind, any neuronanorobot (axonal endoneurobot, synaptobot, or gliabot), and any of their transactional activity can be called in the IPLD for Brain system. In the B/CI group cloudmind, one of the most relevant applications is interfacing thoughts to create new ideas and solve problems.

For the B/CI cloudmind, the IPLD for Brain data structure first and foremost provides a secure content-addressing system in a cloud-based environment. The second benefit of the IPLD for Brain data structure is forced interoperability. Any digital content on the cloudmind brain system is interoperable. Just as one EMR blood pressure reading in the metric system is sharable with another per compatible formats, so too ideas can be better collaborated with compatible formatting. Thoughts are digitally instantiated in the B/CI cloudmind system anyway, and therefore can be easily interfaced with each other in team collaboration. The overlay of the interoperable data structure protects the integrity of the underlying content, in this case the natural and original way that an individual mind thinks about and approaches a problem, yet allows the possibility of interoperating with the cloudmind so that ideas can be aligned at a formatting level for more effective collaboration. The aim of IPLD for Brain is to reach peak performance cloudminds more quickly by reducing basic understanding requests such as "say more about that" or "what do you mean?" Each idea in the B/CI cloudmind could have its own content-addressable location that is called in the hash-linked IPLD for Brain data structure.

14.6.3.1 The Brain is a Merkle Forest of Ideas

The brain is essentially a Merkle forest of ideas. A Merkle forest is a group of Merkle trees, each of which calls an arbitrarily-large thought trajectory, and which can be rendered digitally compatible through multi-hash protocols and Merkle roots. A Merkle root is a top-level hash that calls an underlying data structure. For example, blockchains work in the structure of Merkle trees that roll up to a top-level Merkle root. One top-level Merkle root calls the entire database of all Bitcoin blockchain transactions that have occurred since inception in January 2009. As of April 22, 2020, the Bitcoin data structure comprised over 627,000 transaction blocks (each with a few thousand transactions) (https://blockexplorer.com/). The entire database of transactions can be called by one hash code that is 64 characters in length (the Merkle root). Likewise, in a hash-linked data structure, there can be one top-level Merkle root that calls the entire underlying data corpus such as all Github code or all Pubmed publications. A multi-hash protocol allows interoperability between different hashing algorithms.

In a data structure in which all content items are compatibly addressed, there is no limit to the total amount of data that can be rolled up and called with a short command. An entire brain can be called with a Merkle root, and likewise a cloudmind. A cloudmind effectively becomes a Merkle forest of Merkle trees, all compatibly accessible through the hash-linked data structure of IPLD for Brain. The Merkle root system of data organization allows an arbitrarily-large data store to be called with a single hash code. Just as temperature is a short code that calls the thermodynamic situation of septillions of air particles circulating in a room, and the surface theory in the AdS/CFT correspondence calls the messy interactions of the bulk volume in one fewer dimensions, the Merkle root likewise calls an arbitrarily-large data store.

Further, the Merkle tree structure of hashes is not merely a content addressing system that calls an entire data structure with one short code, it is an active cryptographic security platform. Each call to the data structure performs a cryptographic check by re-running the hash functions to confirm that the underlying data has not changed. The software automatically compares the top-level hashes of the hashed content in the data structure (transaction blocks in the case of Bitcoin) to confirm that there has been no change to the integrity of the underlying data, not even one bit at any location in the entire 627,000 block Bitcoin data structure, for example. The live cryptographic checking of the Merkle root functionality of data structures like IPLD for Brain is crucial to the ongoing security of B/CI cloudminds and engendering participant trust.

IPLD allows the whole web (of compatibly-addressed content), or in the case of IPLD for Brain, a whole mind or a whole cloudmind, to be called with one Merkle root, and checked for data integrity with real-time cryptographic security. The sweeping implication of IPLD is that there could be one top-level hash for the entire internet, which corresponds to all of human knowledge, and likewise one top-level hash that corresponds to an entire brain.

Seeing a brain as a Merkle forest of ideas is a conceptualization paradigm for the implementation of individual and group B/CI cloudminds. In IPLD for Brain, a brain becomes a Merkle forest of Merkle trees, namely a hash-linked data structure that can be connected through multi-hash protocols (to link different hashing algorithms and content trees in the Merkle forest of ideas). An entire brain area, brain, or group of brains in the B/CI cloudmind can be content-addressed in the IPLD for Brain hash-linked data structure. IPLD for Brain is precisely the kind of secure, interoperable, scalable infrastructure needed to enact the B/CI cloudmind.

It has been proposed that thinking could be instantiated in a blockchain, in the brain as a DAC concept (DAC: decentralized autonomous corporation; a collection of automated smart contract programs) (Swan, 2015b). IPLD for Brain is essentially the Brain DAC II in the sense of being able to realize B/CI group cloudminds. The advance provided by IPLD for Brain is that numerous brains can be multi-threaded for collaborative endeavor. One first task of IPLD for Brain might be attempting to log the estimated 60,000 thoughts per day that each mind has (Al-Ghaili, 2017), and identifying which might be most useful for novel ideation.

14.6.4 Cloudmind Activities: What does the B/CI Cloudmind do?

Assuming that B/CI cloudminds can be made possible, the question arises as to what they will do. The immediate objective of the B/CI is to map, monitor, cure, and enhance neural activity. At the more abstract level of everyday activity, the purpose of the B/CI is to facilitate human productivity, well-being, and enjoyment, which could be measured in the extent to which Maslow's hierarchy of needs is fulfilled (Figure 20).

Maslow Tiers	Objective	B/CI Measure
Maslow 1	Physiological survival	Energy, glucose, oxygen, ATP
Maslow 2	Psychological well-being	Neurotransmitter balances
Maslow 3	Self-actualization	Ideas, neurotransmitters, energy
Beyond-Maslow	New levels of achievement	Ideas, new cloudmind design

Figure 20. Maslow's Hierarchy of Needs and Beyond.

Maslow's hierarchy of needs is a tiered structure which comprehensively articulates the different levels of human needs (McLeod, 2007). Maslow identifies multiple levels which are consolidated here into three tiers as pictured. Maslow 1 is physiological survival needs for food, water, warmth, sleep, sex, and security. Maslow 2 is psychological needs for belonging, acknowledgement, and love. Maslow 3 is self-actualization needs for achievement, creativity, and the realization of one's potential. A hierarchy is implicated in that lower-level needs must be met before progressing to the next tier. Pursuing interesting projects (Maslow 3: self-actualization) makes little sense if one is worried about food and housing for the night (Maslow 1: physiological survival). B/CIs could track the fulfillment of Maslow's hierarchy of needs (physiological survival, psychological well-being, and self-actualization) via biological cues logged by the B/CI, and formalized in the notion of Maslow smart contracts (Swan, 2019).

Since the cloudmind may be a collaboration of human and machine minds, its capacities could progress beyond those articulated in Maslow's hierarchy of needs, as contemplated in the "beyond-Maslow" category. Some of the potential areas of beyond-Maslow development could include scientific advance, cloudmind learning, and the cloudmind itself as a platform. In the area of scientific advance, cloudminds could pursue different ways to integrate research findings and make them more broadly accessible to address the challenge of reductionist findings and the practical impossibility of keeping up with scientific publications. There could be journal club cloudminds that perform literature summaries, write review papers, and generally engage in knowledge stewarding activities as next-generation librarians or information scientists. These kinds of integrative activities could themselves result in new findings (Chiang, 2002, 47).

Regarding learning, the B/CI is envisioned as a heightened learning tool that might support beyond-Maslow objectives including through the eventual direct neural transfer of information. All of the world's knowledge might be modularized for uptake and propagation. *Knowledge modules* emerge as standardized units of information required for the understanding of a certain topic, packaged into consumable units and distributable globally. Coursera (and other MOOCs (massive open online courses) are platforms that deliver knowledge modules. The most successful (widely-propagated) knowledge module (and cloudmind community prototype) is Andrew Ng's machine learning course, with over 3 million enrolled students as of April 2020 (Ng, 2020). Just as there are fungible global equivalents for healthcare (Swan, forthcoming), there can be fungible equivalents for learning, implemented via B/CI. Knowledge modules could be organized into structured paths for mastery (accredited degrees and certifications) deploying the same kind of leveling-up gamification techniques that have proven successful in learning communities as diverse as Toastmasters and World of Warcraft.

Considering the cloudmind itself as a platform, the beyond-Maslow objective would be to design and test new versions of intelligence with cloudminds. B/CI cloudminds could be used to instantiate different proposed models of artificial intelligence (AI). For example, one idea is to boot up Kant and Hegel's models of consciousness, and various AIs envisioned in science fiction (for example, the multi-party society articulated by Max Harms (2016)). With this recursive objective, the cloudmind could help produce new and better cloudminds.

14.6.4.1 Classes of Cloudminds

A variety of classes of cloudminds may evolve with different purposes (Figure 21).

	Cloudmind Class
1	**Question-asking cloudminds:** Question-asking cloudminds focus on generating good questions. Contemplating the human-machine partnership, futurist Kevin Kelly notes that humans are good at

	asking questions, and machines are good at answering them. (Neurocurrency: questions)
2	**Problem-solving cloudminds:** Working on a list of unsolved problems in various fields, problem-solving cloudminds might be a workhorse class of cloudminds, consolidating wisdom-of-the-crowds talent together to solve the thorniest problems available. There could be the Polymath Fields Medal MathNet, Quantum Gravity, and Anti-aging Cellular Therapies cloudminds. Various methods might be applied (deduction, induction, abduction). (Neurocurrency: ideas, solutions, publications)
3	**Journal Club/Affinity (special-interest) cloudminds:** Any variety of special interest cloudminds might focus on topics such as space exploration, transnational political systems, environmental sustainability, longevity, economics, painting, and music theory (Neurocurrency: ideas, publications)
4	**Transparent shadowing cloudminds:** Transparent shadowing cloudminds could be a class of cloudminds devoted to the real-time immersive experience of other humans (on a permissioned basis), experiencing another person's life through their own eyes for learning, collaborating, apprenticing, and sharing experience. (Neurocurrency: learning, experience, empathy units)
5	**Random cloudminds:** Variety and surprise are crucial and the random cloudminds could be a serendipity-class cloudmind. This is reminiscent of the virtual entertainment device (stimsim) in *Neuromancer* (Gibson, 1984), a ~250 channel device (i.e. a lot at the time), including a channel for not knowing what to select. (Neurocurrency: enjoyment units)

Figure 21. Different possible Classes of Cloudmind.

Risks and Limitations

The biggest potential risk and limitation of the B/CI is security. There is "no neural dust without neural trust." Security plays an outsized role in the implementation of the B/CI because the brain is an extremely sensitive area for intervention. Given this sensitivity, the knee-jerk reaction is to reject any kind of brain-connected internet device, much less on-board nanorobots, and the monitoring, sharing, and manipulation of neural information. Especially in an era of heightened internet privacy and cybersecurity threat, the last thing that seems to make sense is interfacing the most sensitive asset humans possess, their brain, to the internet. Therefore, cybersecurity concerns must be resolved in a robust manner or the B/CI will be a non-starter.

One indication of the sensitivity of the brain is how individuals respond to information about their genetic profile for Alzheimer's disease. A landmark study, the REVEAL study, shared genomic information regarding Alzheimer's disease with individuals (Green et al., 2009). Although notoriously intransigent to health-related behavioral modification, over half of individuals finding out that they were at high risk for Alzheimer's disease changed their behavior as a result, using medication, vitamins, diet, and exercise (Chao et al., 2008, 3). Genomic sequencing pioneer Craig Venter, likewise engaged in interventional activity upon finding out that his own genome (that he had sequenced) was positive for the Alzheimer's disease-related APOE 4 mutation (Nave, 2016).

This work therefore proposes B/CI Neural Trust as a new concept in internet security adequate to the realization of the B/CI. B/CI Neural Trust provides a specific solution to deliver neural trust in the B/CI that is both hardware and software based. Neural Trust involves hardware trust conferred by nature's quantum information features and software trust provided by the blockchain operating software. Trust is conveyed in the quantum computing hardware solution for the B/CI through nature's built-in security features that apply to any quantum information domain such as no copying and no measurement principles. Trust is conveyed by the operating software proposed for the B/CI through the security and privacy features built into blockchains.

Beyond security concerns, the most substantial risk attached to this work is that the B/CI has the current status of being a speculative proposal without immediate practical development possibilities. Only the core BCI exists for basic computerized cursor control and neuroprosthetic administration. However, the point is not to dismiss this work as science fiction or navel-gazing since it is important to think through future technologies involving the brain in great detail. The B/CI and B/CI cloudmind are technologically complex concepts with many aspects of their practical interface to human brains to be considered. It is crucial to consider these kinds of future technologies in detail with many scenarios, design specifications, and implementation plans before their actual advent. Considering potential technologies ahead of their implementation could facilitate the development of social maturity and responsible technology use that often lags the invention of a technology. Further, considering sophisticated projects such as the B/CI and the B/CI cloudmind highlights what may be possible in the near-term, for example predictive data analysis of existing BCIs in regard to power-consumption and parts failure rates.

A second class of risks pertains specifically to the proposals in this work, that they may be ill-founded, infeasible, or inaccurate. Admittedly, this is a possible risk, however, the overall value of this work may be the gist of the theoretical ideas. It is expected that technical details may shift in the potential realization of B/CIs. Quantitative estimates of brain activity are an early-stage analysis and may vary widely in actuality. Also, given the sensitivity of the human brain, it may never be deemed appropriate to intervene, or at least not for a very long time (direct genomic intervention, for example, has been curtailed due to early missteps involving the death of a clinical trial participant in 1999 (Branca, 2005)). The theoretical analysis proposed here may prove faulty in different ways. For example, a more straightforward control theory not based on the AdS/CFT correspondence may present itself for managing between macroscale reality and quantum mechanical domains if quantum computing were to proceed more substantially. Any variety of software-based control theories might be indicated. Blockchains are complicated to understand and might not survive, although large-scale autonomously-operating global smart network computing software might continue to use some of the same core features.

A third class of risks pertains to the asymmetric treatment of opportunity and threat in this analysis. Many positive possibilities for the B/CI and the B/CI cloudmind are presented, but a corresponding and equally weighted consideration of the potential risks is not elaborated or resolved. Any technology is dangerous to the extent that the brain is involved. In an era of routine cybersecurity attacks and the inability of institutions and individuals to protect electronic data on personal computers and smartphones, it is naïve to think that anyone would provide internet access to their mind. In response, the B/CI and B/CI cloudmind are future-class technologies and it is too early in the development cycle for a comprehensive risk assessment, also it is noted that the B/CI is a non-starter without an adequate security solution. Future work necessary to B/CI implementation would certainly involve a more comprehensive risk analysis. Meanwhile, there are some science fiction examples of scenarios to avoid in B/CI design in terms of the disruptive effects of neural hacking (for example Greg Bear's *Slant* (1998)).

A final class of risks relates to the sequenced arrival of new technologies. Predictions involving future technologies are notoriously difficult. Further compounding predictions related to any one technology is the issue of technology sequencing, meaning the order of arrival of different potential future technologies. The B/CI might be obviated by the advent of other technologies. For example, if non-invasive personal connectome mapping were to become possible by a non-B/CI means, there could be digital copies of each person's brain. This could make biological intervention much less desirable, and supersede the biological brain with the digital version as the desired platform for all manner of enhancement and collaboration. The brain might be re-platformed to the digital environment without the need for B/CIs.

Conclusion

The full suite of BCI technologies includes the core existing BCI (brain-computer interface) for directing computer cursors and neuroprosthetics, and the envisioned cloudmind B/CI (brain/cloud interface) for safely connecting one or more minds to the internet cloud. The B/CI would be implemented through an ecosystem of tiny medical nanorobots seamlessly embedded in the brain. The neural signaling of the brain would be platformed in an alongside computational environment to simulate and enhance the brain's native activity. At least three neuronanorobot species have been outlined to comprise the B/CI. These are axonal endoneurobots corresponding to the axons that generate electrical pulses (action potentials) in neural signaling, synaptobots residing in and around the synaptic terminals that transmit and receive signals, and gliabots linked to the glial cells that facilitate signal transmission and clean-up. There would be a one-to-one correspondence between neural cells and neuronanorobots, meaning a neuronanorobot complement for each of the 86 billion neurons, 86 billion glial cells, and 200 trillion synapses.

The technical requirements for the realization of the B/CI are substantial. This work proposes quantum computing as the hardware platform for the B/CI (including via the possible advent of global quantum photonic networks), together with a holographic control theory (based on the AdS/CFT correspondence) as the lever for macroscale control of the quantum computing cloud environment (the AdS/CFT correspondence is a universal control theory to orchestrate macroscale-quantum domains), and a bio-blockchain neuroeconomy as the operating software of the in-brain B/CI neuronanorobot network. Security is a paramount concern for B/CI implementation and neural trust is conveyed first as hardware trust from nature's built-in quantum security features (such as the no cloning and no measurement principles) and second as software trust from the cryptographic properties of blockchains.

In the greater implementation of group cloudmind B/CIs for interactive collaboration to enhance productivity, well-being, and enjoyment, some of the additional benefits of instantiating the neural signaling platform in the digital environment can be seen. Lower-level barriers to group collaboration can be overcome such as credit assignment and the sheer feasibility of multi-threading thousands of minds into a coherent whole. A richer level of communication may be possible with B/CIs such as direct neural transfer, and because in the digital environment of coded thoughts, formatting standards can enforce a basic level of interoperability that might reduce the possibility of misunderstanding and improve the ability to collaborate ideas.

One on hand, the B/CI is needed merely to cope with the situation of modern reality in which the development of science and technology outpaces that of biology. Beyond that, the greater stakes of the cloudmind B/CI for group collaboration (the "ten billion synapse world mind") are the possibility of making progress towards the achievement of a Kardashev-plus society that is able to marshal all available tangible and intangible resources by mental and physical means for the flourishing of society.

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Glossary

AdS/CFT Correspondence: The AdS/CFT (Anti-de Sitter space/Conformal (basic) Field Theory) correspondence (also called the holographic correspondence, gauge-gravity duality, and the bulk-boundary relation) is the claim that in any physical system, there is a correspondence between a volume of space and its boundary region such that the interior bulk can be described by a boundary theory in one fewer dimensions.

BCI (Brain-Computer Interface): A BCI (brain-computer interface) is a direct communication pathway between a wired brain and an external device via EEG (electroencephalography).

B/CI (Human Brain/Cloud Interface): A B/CI is a proposed technology that would interface the human brain with the internet cloud using neuronanorobots.

B/CI Cloudmind: A B/CI cloudmind is one or more minds connected to the internet cloud on an individual or group basis for activities related to productivity, well-being, and enjoyment.

BCI Technologies: BCI technologies are the suite of technologies including the core BCI and the individual and group cloudmind B/CI that safely connect the mind to the internet.

Bio-blockchain: A bio-blockchain is a blockchain implemented in the biological context.

Bio-correspondence: The Bio-correspondence is an interpretation of the AdS/CFT correspondence in a biophysical context such as the dual of the neuron-synapse system.

Black Hole Information Paradox: The black hole information paradox asks how it is possible for information to exit from a black hole, since information cannot escape from black holes (per General Relativity), but Hawking radiation does emanate from black holes, which conflicts with the no-cloning theorem of quantum information (per Quantum Mechanics).

Blockchain (Distributed Ledger Technology): A blockchain (distributed ledger technology) is a secure automated cryptographic system for internet-based value transfer.

Cloudmind: A cloudmind is one or more minds connected to the internet cloud. A cloudmind might be comprised of an individual mind operating on the internet, or multiple human and machine minds participating in a collaborative activity. 'Mind' generally denotes an entity with processing capacity (not necessarily a biological mind that is conscious).

Complex Adaptive Systems: Complex adaptive systems are those that are non-linear, emergent, open, unknowable at the outset, interdependent, and self-organizing.

ComplexityTech: A ComplexityTech (complexity technology) is a technology for managing complexity and complex adaptive systems, whose behavior is non-linear and unpredictable.

Computational Complexity: Computational complexity is a schema of the tiers of the necessary computational resources (in time and space) needed to calculate a given problem.

Connectome: The connectome is a wiring diagram of the brain, the functional processing framework and structure of the brain in full spatial and temporal resolution.

Gauge-Gravity Duality: Gauge-gravity duality is an interpretation of the AdS/CFT correspondence per the intuition that both gravity (General Relativity) and gauge theory (Quantum Mechanics) are field-based phenomena at the scale of gauge theory (1×10^{-15} m), and therefore might be joined through the correspondence.

Hash Code: A hash code is a function used to map data of arbitrary size onto data of fixed size.

Holographic Principle: The holographic principle is the notion of reconstructing a 3D volume on a 2D surface (like a hologram), and indicates two valid views of the same phenomenon.

IPLD (InterPlanetary hash-Linked Data structure): IPLD is an internet-wide file system overlay for access to compatibly-addressed content; a data standard for calling any variety of the vast corpora of internet-based data structures such as Github code and Pubmed health publications. URL links are hashed for data security and to provide the interoperable format.

IPLD for Brain: IPLD for Brain is specialized application of IPLD as a B/CI data standard.
Kardashev-plus Society: A Kardashev-plus society is one that is able to marshal all tangible and intangible resources, including energy, for the surviving and flourishing of populations in all manner of productivity, well-being, and enjoyment.
Kardashev Civilizations: The Kardashev civilizations is a scale that measures societal advancement on the degree of energy resources controlled. A Type I civilization is able to use all available sunlight on the planet, Type II all the energy the sun produces, and Type III the energy of the entire galaxy. Humanity is currently estimated to be 0.7 on the scale.
Knowledge Module: A knowledge module is a standardized unit of information required for the understanding of a certain topic, packaged into a consumable unit and globally distributable.
Medical Nanorobots: Medical nanorobots are nanorobots (molecular machines at the nanoscale (1×10^{-9} m)), designed to complement native cells and perform medically-related tasks in the body. Proposed species include respirocytes, clottocytes, vasculoids, and microbivores.
Merkle Forest: A Merkle forest is a group of Merkle trees calling multiple content trajectories.
Merkle Root: A Merkle root is a top-level hash (e.g. 64-character short code) that calls an entire underlying data structure (Merkle tree), for example an entire database of transactions.
Neurocurrency: A neurocurrency is a resource (e.g. ions) used to execute a neural function.
Neuroeconomy: The neuroeconomy is a multi-agent economic system used to operate neural activities based on goal-directed behavior in transactions denominated in neurocurrencies.
Neuron: A neuron is an electrically-excitable cell that communicates with other cells by sending a signal called an action potential to other neurons across specialized connections called synapses, and is comprised of a cell body (soma), a long thin axon insulated by a myelin sheath for outbound signaling, and multiple dendrites for receiving inbound signals.
Neuronanorobots: Neuronanorobots are medical nanorobots designed specifically for operating in the brain. Three species or neuronanorobots have been proposed to correspond to the phases of the neural signaling process: axonal endoneurobots, synaptobots, and gliabots.
Payment Channel: A payment channel is a network overlay that allows parties to pre-contract with one other to automatically replenish resources or rebalance accounts.
Quantum Computing: Quantum computing is information processing at the quantum scale of atoms (1×10^{-9} m) particularly via SEI properties (superposition, entanglement, interference).
Quantum Internet: The quantum internet is a next-generation internet proposal that would feature secure end-to-end communication based on quantum switches and routers, quantum key distribution, quantum processors, and quantum memory.
SEI Properties: The SEI properties (superposition, entanglement, and interference) are the properties of quantum objects (atoms, ions, photons) that facilitate quantum computing.
Smart Contract: A smart contract is blockchain-based pre-specified programmatic instructions.
Smart Network: A smart network is an automated global network-based computational technology such as blockchains, deep learning nets, UAVs, and automated trading networks.
Synapse: A synapse is a structure that permits a neuron to pass an electrical or chemical signal, mainly to another neuron, or possibly to another cell or the intercellular environment.
Temperature Term: A temperature term is an aggregate informational state of a system that might be employed as a control lever. Examples: Merkle root, AdS/CFT surface theory.
Zero-knowledge proof: A zero-knowledge proof is a proof that reveals no information except the correctness of the statement. Data verification is separated from the data itself, conveying zero knowledge about the underlying data, thereby keeping it private.

Appendix 1: Relative Size of Neural Entities and Neuronanorobots

This analysis suggests that the axonal endoneurobot and the gliabot could be similar in size to other medical nanorobots, about 1,000 nm or larger, but that the synaptobot would need to be much smaller, perhaps on the order of 5-300 nm, given the small size of the synaptic area in which it is to be housed. Several species of medical nanorobots have been proposed for health-related activities in the body (generally 1,000-3,000 nm in size), as listed in Figure A1-1.

Entity	Size (microns)[5]	Size (nm)	Reference
Human Hair and Circulatory System			
Human hair	100 microns[6]	100,000 nm	Ley, 1999
Red blood cell	7 microns	7,000 nm	Freitas, 2012, 69
Smallest capillaries	3 microns	3,000 nm	Freitas, 2012, 69
Medical Nanorobots			
Clottocytes (artificial platelets)	2 microns	2,000 nm	Freitas, 2000
Microbivores (artificial phagocytes)	3.4 microns	3,400 nm	Freitas, 2005
Respirocytes (artificial red blood cells)	2-3 microns	2,000-3,000 nm	Freitas, 2012, 69
Vasculoids (cell transporter boxcar)	100 x 6 microns	100,000 x 6,000 nm	Freitas & Phoenix, 2002
Nanorobot components		1-10 nm	Freitas, 2012, 69
Vascular Cartographic Scanning Nanodevice (for connectome mapping)	1 micron	1,000 nm	Domschke & Boehm, 2017

Figure A1-1. Relative Size of Circulatory System Entities and Medical Nanorobots.

A similar analysis can be performed for neuronanorobots. The objective is to clarify the implied size of neuronanorobots given the size of the neural areas in which they are to be housed. The relevant neural cells are listed in Figure A1-2. Whereas there is a lot of room in the neuronal cell body at the start of the axon where the axonal endoneurobot is to be located, and in the glial cells for the gliabot, there is very little space available in the synaptic terminal areas for the synaptobot. There is room for a 1,000 nm nanorobot in the 10,000-25,000 nm neural cell body and the 15,000-30,000 nm glial cell. However, the synaptic terminal areas are only 100-1,000 nm^3 in size, so an embedded synaptobot would need to be perhaps 30-300 nm in size.

Neural Cells	Size (microns)	Size (nm)	Reference
Neuron cell body (soma)	10-25 microns	10,000-25,000 nm	Chudler, 2009
Neuron cell body nucleus	3-18 microns	3,000-18,000 nm	Chudler, 2009
Pre-synaptic and post-synaptic area	0.1-1 μm^3	100-1,000 nm^3	Kleinfeld et al., 2011
Synaptic cleft		20-50 nm	Scimemi & Beato, 2009, 290
Glial cells: Astrocytes	40-50 microns	40,000-50,000 nm	Parent, 1996
Glial cells: Microglial cells	15-30 microns	15,000-30,000 nm	Kettenmann & Verkhratsky, 2011

Figure A1-2. Relative Size of Neural Cells.

The precise size and function of various areas involved in pre-synaptic and post-synaptic signaling terminals is an active area of research. The overall synapse is comprised of the pre-

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[5] Regarding units: 1 micron = 1 micrometer = 1 μm. A micron is a standard unit of length equaling 1 x 10^{-6} meter (SI standard prefix "micro-" = 10^{-6}) for one millionth of a meter (or one thousandth of a millimeter, 0.001 mm) which is equal to 1,000 nanometers. A nanometer is one billionth of a meter (1 x 10^{-9} meter).
[6] Range: 17-181 μm.

synaptic terminal, the synaptic cleft, and the post-synaptic terminal. Although some pre-synaptic terminals are micron-sized (1,000 nm^3) (Fig. 2A, 2B), the vast majority of are less than 0.1 µm (less than 100 nm^3) (Fig. 2C) (Kleinfeld et al., 2011). The synaptic cleft is 20-50 nm (Scimemi & Beato, 2009, 290). Synaptic vesicles in the terminal area are of two varieties, either large (200 nm^3) or small (50 nm^3) (https://web.williams.edu/imput/IIA1_right.html), 40 nm^3 in the visual cortex for example. A particular apparatus called the post-synaptic density is a protein-dense area attached to the post-synaptic membrane, and is 250-500 nm in diameter (Meyer et al., 2014). The post-synaptic density is located across from the active zone of the pre-synaptic terminal, and orchestrates signal reception, becoming enlarged during synaptic plasticity (the long-term potentiation or depression of synapses). In general, the size of pre-synaptic and post-synaptic terminals is dynamic, and expands and shrinks during the signaling process. The signaling of many different proteins is implicated in the process. For example, Sonic hedgehog (Shh) signaling has an expansionary effect on the pre-synaptic terminals of both glutamatergic and GABAergic synapses in adult hippocampal neurons (Mitchell et al., 2012, 4208). Glutamate (excitatory action) and GABA (inhibitory action) are the two most common neurotransmitters in the brain, comprising 90 percent of neurotransmitter activity.

Finalizing the neuronanorobot size analysis, the axonal endoneurobot and the gliabot could be analogous in size to other nanorobots, about 1,000 nm (Figure A1-3). The implied size for the synaptobot, though, is much smaller, 30-300 nm if housed in synaptic terminals, and smaller still if located in the synaptic cleft, perhaps 5-10 nm (the size of a nanorobot part).

Neuronanorobot	Location	Size of Location	Size of Neuronanorobot
Axonal endoneurobot	Neuron cell body (soma)	10,000-25,000 nm	1,000 nm
Synaptobot: pre-synaptic terminal	Post-synaptic terminal	100-1,000 nm	30-300 nm
Synaptobot: synaptic cleft	Synaptic cleft	20-50 nm	5-10 nm
Synaptobot: post-synaptic terminal	Post-synaptic terminal	100-1,000 nm	30-300 nm
Gliabot	Glial cells	15,000-30,000 nm	1,000 nm

Figure A1-3. Implied Size of Neuronanorobots as dictated by Size of Housed Location.

Determining neurotransmitter concentrations in synaptic vesicles has been a helpful first step in quantifying the size and scope of activity in synaptic signaling. Estimated concentrations of primary neurotransmitters acetylcholine and glutamate appear in Figure A1-4.

Neurotransmitter	Concentration (mM)	Reference
Acetylcholine	0.3 mM - 260 mM	Scimemi & Beato, 2009, 290
Glutamate	60 mM - 150 mM	Scimemi & Beato, 2009, 291

Figure A1-4. Neurotransmitter Concentration (millimoles (mM)) in Synaptic Vesicles.

As background for the neuronanorobot size analysis, neurons are the main component of the nervous tissue, electrically-excitable cells that signal to each other through synapses. Based on function, there are three main kinds of neurons (Figure A1-5). Motor neurons are responsible for motor control, which is the planning and coordination of movement, and also for reasoning, language, and higher-level cognitive functioning. Sensory neurons receive and process sensory information, including visual stimulus. Interneurons connect neurons to other neurons within the same brain region to coordinate activity among groups of neurons.

Neurons	Function

Motor neurons	Control the activity of muscles, and higher-level cognitive functions such as reasoning and language (most numerous by far)
Sensory neurons	Detect and respond to internal and external stimulus
Interneurons	Moderate reflexes and coordinate activity between neurons

Figure A1-5. Neurons by Type and Function.

Glial cell processing is on the very small scale of sub-cellular processing. However, glial cells may be ideally poised for intervention given their extensively catalogued operations and locational adjacency to neurons. It may be easier and safer to intervene with glial cells as the support environment for neurons rather than directly with the neurons themselves. The different types of glial cells in the central and peripheral nervous system are listed in Figure A1-6.

Glial Cells	Percentage	Function
Central Nervous System		
Oligodendrocytes	45-75%	Provide myelination to coat axons, insulate axons
Astrocytes	19-40%	Regulate chemical environment by removing excess potassium ions and recycling neurotransmitters; ATP, IP3 (messenger enzymes), calcium
Microglia	<10%	Destroy pathogens, phagocytose debris; microglia deficiency is associated with Alzheimer's disease, Parkinson's disease, ALS
Ependymal cells		Secrete cerebrospinal fluid and produce the blood-brain barrier
Radial glia		Neuroepithelial development and neurogenesis
Peripheral Nervous System		
Schwann cells		(similar to oligodendrocytes) Provide myelination to axons in the peripheral nervous system, phagocytose to remove debris
Satellite cells		Surround neurons in sensory, sympathetic, and parasympathetic ganglia; regulate external chemical environment; respond to ATP and calcium ions
Enteric cells		Provide homeostasis and muscular digestive processes, located in the intrinsic ganglia of the digestive system

Figure A1-6. Glial Cells by Type, Frequency, and Function.

Glial cells are implicated in B/CI design as follows. Oligodendrocytes generate the myelin sheath to protect axons and are in close proximity to axons. Astrocytes are active around the synaptic cleft in facilitating cell signaling. Microglia act as an immune system to identify and destroy pathogens, and could be used in B/CI projects to target neurodegenerative disease. Microglial interventions might be used to address Parkinson's disease, Alzheimer's disease, and ALS. The overall ratio of neurons to glial cells is estimated as a one-to-one correspondence (each having a population of 86 billion cells). However, there is a great deal of specificity depending on the brain region (Azevedo et al., 2009). In the cerebral cortex, the gray matter neurons to glial cell ratio is thought to be 1.48 (and the overall cerebral cortex 3.72). The cerebellum has only a 0.23 ratio of neurons to glial cells (relatively few glial cells). The basal ganglia, diencephalon, and brainstem region, on the other hand, have an 11.35 to 1 ratio (Figure A1-7).

Brain Area	Glia-to-Neuron Ratio	Glia	Neurons
Cerebral cortex			
Grey matter and white matter	3.72	60.84 bn	16.34 bn
Grey matter	1.48		
Cerebellum	0.23	16.06 bn	69.03 bn
Basal ganglia, diencephalon, brainstem	11.35		

Figure A1-7. Glia-to-Neuron Ratios by Brain Area.

Appendix 2: B/CI Technical Requirements and Implementation Phases

This Appendix discusses some of the prominent technical requirements for B/CI implementation such as bandwidth and information transfer, transaction processing, and power, and outlines a phased implementation plan. A framing specification of the technical requirements for a long-term, non-destructive, real-time human brain interface with the cloud appears in Figure A2-1 (Martins et al., 2019, 9).

	Neuronanorobot Requirement
1	Ultrahigh-resolution mobility
2	Autonomous or semiautonomous activity
3	Non-intrusive ingress/egress into/from the human body
4	Robust information transfer bandwidth for interfacing with external computing systems

Figure A2-1. B/CI Technical Requirements.

Bandwidth and Information Transfer

The B/CI neuronanorobots would need an extremely fast wireless transmission capability, on the order of 6×10^{16} bits per second (Martins et al., 2019). Synaptically-processed and encoded human-brain electrical information would be sent via auxiliary nanorobotic fiber optics (30 cm^3) with the capacity to handle up to 10^{18} bits/sec and provide rapid data transfer to a cloud-based computing environment for real-time brain-state monitoring (Martins et al., 2019).

To some degree, existing BCIs for controlling neuroprosthetics through electrical pulse brain signals are offering internet connectivity. For example, Hanger, a Texas-based provider of orthotic aids and prosthetic limbs collects near real-time data regarding usage and mobility, connecting directly to AT&T's 4G Long Term Evolution for Machines (LTE-M) network (Scroxton, 2018). Personal data protection standards have been called for in the design standards of BCI medical applications in signal-acquisition hardware and software that is convenient, portable, safe, and able to function in all environments (Shih et al., 2012).

It is estimated that full-fledged B/CIs will require broadband access with extremely high upload and download speeds compared to today's rates. Internet networks are starting to accommodate two-way transfer. Although initially designed for asymmetric information download from servers to clients, communications networks now support large volumes of data upload from IoT sensors and consumer devices. The current data rate for B/CI-type upload is 24 Mb/second, via both Bluetooth 4.0 (for IoT) and IEEE 802.11n low-power Wi-Fi technology (for body area networks (BANs)) (Zao et al., 2014). Next-generation communications networks such as 5G (100-200 MB download speeds) and farther-future terahertz networks (100 GB data links) may play a role in the ultra-high-speed wireless data networks of the future that could enable the required upload and download speeds for B/CIs.

Intrinsic Neural Firing Rates

The intrinsic neural firing rates of the human brain could be used as an input to calculate the transaction processing capacity required by the B/CI. One estimate of the firing rate in the human neocortex is 4 spikes per second (Attwell & Laughlin, 2001). In other animal species, a study of the visual cortex found rates of neural firing averaging 3-4 spikes per second for cats, and 14-18 spikes per second for macaques, and another found 9 spikes per second for cats (Baddeley et al., 1997). Other work in the neocortical simulation efforts of the whole brain emulation project notes the difficulty of estimating an average firing rate due to the non-linear behavior of one neuron triggering another (Gerstner et al., 1997). Another variable in the firing rate of neural signaling is the necessary refractory period, which is a few milliseconds in humans (Nicholls et al., 2012, 14). In general, 20-60 percent of the brain's energy budget is consumed by signaling purposes, either via action potentials or by synaptic transmission (Figure A2-2).

Brain Function	Energy
Action Potentials	47%
Synaptic Transmission	40%
Neural Resting Potential	10%
Glial Resting Potential	3%

Figure A2-2. Energy Budget used for Signaling in the Brain (Attwell & Laughlin, 2001).

The state-of-the art of the world's largest transaction processing systems accommodate 175,000 transactions per second (Figure A2-3). This implies that if neurons were firing at a rate of once per second (although it might be higher), then firing for ~500,000 (0.001%) of the brain's 86 billion neurons could be handled in contemporary transaction systems.

	Transaction System	Average TPS	Peak TPS	Year	Reference
1	Visa	2,000	24,000	2011	Visa, 2011
2	Alipay (China)	120,000	175,000	2017	Skinner, 2017
3	Facebook	175,000	N/A	2017	Ehrsam, 2017
4	World's largest banks	100,000	N/A	2020	Blaschka, 2020

Figure A2-3. Contemporary Transaction System Analysis of Transactions per Second (TPS).

In-situ Power

A key design requirement for neuronanorobots is the ability sustain themselves by foraging for fuel in the local biological environment. Estimates suggest that nanorobots of the standard estimated size (1,000 nm) could produce several tens of picowatts of power from oxygen reaching their surface naturally in the blood plasma (Hogg & Freitas, 2009). This would provide enough power for the steady state activities of the nanorobot. If further equipped with pumps and tanks for onboard oxygen storage, nanorobots could possibly collect enough oxygen to support burst power demands two to three orders of magnitude larger. Software updating and lifecycle management are other design considerations for autonomous nanorobot operation.

B/CI Implementation

The B/CI project would be implemented in phases (Figure A2-4). The basic functionality of the minimal implementation is highlighted in the Phase I column, and the full-fledged version in the Phase II column. Although neural signaling is both electrical and chemical, the initial B/CI implementation could be on the basis of electrical signaling alone (Martins et al., 2019, 10).

B/CI Function	Phase I	Phase II
Scope of signaling	Electrical	Electrical and chemical
	Action potentials: Capture electrical signal processing	Neurotransmitters: Capture electrical and chemical signal processing
Temporal processing	Batch upload	Real-time processing
Information transfer	One-way (outbound)	Two-way information retrieval
Scale	Cellular processing: neurons Atomic scale (1 x 10^{-9} m)	Sub-cellular processing: synapses Gauge theory scale (1 x 10^{-15} m)
Focus	Targeted brain regions	Whole brain

Figure A2-4. B/CI Implementation Phases by Functionality.