Designing a New Class of Autopoietic Machines

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August 9, 2021

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***Abstract*— All living organisms are autopoietic and cognitive. Autopoiesis refers to a system with well-defined identity and is capable of reproducing and maintaining itself. Cognition, on the other hand, is the ability to process information, apply knowledge, and change the circumstance A living organism is a unique autonomous system made up of components and relationships changing over time without changing the unity of the system. The genome contains the knowledge that is required to build the components using physical and chemical processes and physical resources. Information processing structures in the form of genes and neurons provide the means to build, operate and manage the stability of the system while interacting with the external world where the interactions are often, non-deterministic in nature and are subject to large fluctuations. Our understanding of how theses information processing structures operate comes from the analysis of the genome, experiments in neuroscience and the studies of cognitive behaviors in living organisms. First, we summarize here, the key learnings that point to how the organism manages both the "self" and its interactions with external world. Second, we use the new mathematics of structural machines, triadic automata, knowledge structures, named sets and cognizing oracle theories to present a model that captures the key features of autopoietic behavior. Finally, we use this model to design digital autopoietic machines by defining a digital genome that uses digital genes (in the form of executable algorithms) and digital neuronal models (in the form of deep learning neural networks) as information processing structures.**

Keywords— Cognition, Computing Models, Deep Learning, Autopoiesis, Knowledge Structures, Structural Machines, Autopoietic Machines.

I. Introduction

Classical computer science with its origins from the John von Neumann's stored program, which implemented the information processing structure based on the universal Turing machine, has given us tools to decipher the mysteries of physical, chemical and biological systems in nature. Both symbolic computing (using algorithmic computations) and sub-symbolic computing (with neural network implementations) have allowed us to model and analyze various observations (including both mental and physical processes) and use information to optimize our interactions with each other and with our environment. In addition, our understanding of the nature of information processing structures using both physical and computer experiments is pointing us to a new direction in computer science going beyond the current AI limitations of lack of transparency and the Church-Turing thesis boundaries of classical computer science dealing with the finite nature of resources.

There are three major contributions to our understanding of what information is, how it is processed into knowledge, how it is communicated and how it is used:

1. Our understanding of the genome, neuroscience and cognitive behaviors of biological systems,
2. Our use of digital computing machines to unravel various mysteries about how our physical world works and to model, monitor and manage it, and
3. A new set of mathematical tools in the form of named sets, knowledge structures, cognizing oracles and structural machines which allow us to not only explain how information processing structures play a key role in the physical world but also to design and implement a new class of digital automata called autopoietic machines which advance our current state of information technologies by transcending the limitations of classical computer science as we practice it today.

While there is a host of literature published in the academic realm dealing with these subjects, this paper is aimed at utilizing the recent results [1-11] articulated eloquently by eminent researchers in these fields. These works refer to various other sources and their own extensive contributions supporting their conclusions.

In section II, we summarize key learnings from the observations in neuroscience on how the brain processes information using the cognitive structures in the form of genes and neuronal networks and uses it to create an information processing physical structure exploiting physical and chemical processes that obey transformation laws of matter and energy.

In Section III we discuss current state of the art of digital information processing structures in the form of symbolic and sub-symbolic computing structures. We point out the limitations of current digital information processing structures to deal with non-deterministic fluctuations in their interactions at scale and their shortcomings in dealing with risk assessment and mitigation in real-time which the living organisms do.

In section IV, we summarize the new unified science of information processing structures, so eloquently articulated by Prof. Mark Burgin and discuss the nature of triadic automata and digital autopoietic machines.

In Sections V and VI, we discuss triadic automata and present a design for the digital autopoietic automata to advance the current state of the art of information processing structures.

In Section VII, we summarize our conclusions and point to further investigations into the theory and practice of digital autopoietic machines.

II. Learnings From Neuroscience and the Study of Cognitive Behaviors

As Stanislas Dehaene [1] points out "Every single thought we entertain, every calculation we perform, results from activation of specialized neuronal circuits implanted in our cerebral cortex. Our abstract mathematical constructions originate in the coherent activity of our cerebral circuits, and of the millions of other brains preceding us that helped shape and select our current mathematical tools." Jeff Hawkins [6] expresses awe at what the cells in living organisms can do. "Cells are simple. A single cell can't read, or think, or do much of anything. Yet, if we put enough cells together to make a brain, they not only read books, they write them. They design buildings, invent technologies, and decipher the mysteries of the universe. How a brain made of simple cells creates intelligence is a profoundly interesting question, and it remains a mystery."

If we carefully study the observations of the brain and the neocortex using PET and FMRI, their interpretations and various theories that have emerged from there, we discern a picture of how living organisms process information, create knowledge about its "life" processes from cradle to grave and execute them exploiting the environment where physical structures enable physical and chemical processes that obey the matter and energy conversion laws of nature. The genome contains the knowledge from the information gained in the process of evolution by the living organisms. In essence, they utilize matter and energy transformations to execute the "life" processes using the information and knowledge they have accumulated through the process of natural selection. The knowledge is organized using genes and the neuronal networks giving rise to both autopoietic and cognitive behaviors of the organism. An autopoietic system is a network of processes that produces the components that reproduce the network, and that also regulates the boundary conditions necessary for its ongoing existence as a network. Cognition, on the other hand [12], is the ability to process information, apply knowledge, and change the circumstance. Cognition is associated with intent and its accomplishment through various processes that monitor and control a system and its environment. Cognition is associated with a sense of "self" (the observer) and the systems with which it interacts (the environment or the "observed"). Cognition extensively uses time and history in executing and regulating tasks that constitute a cognitive process.

We summarize the picture that is emerging from these studies and we refer the reader for the details to the books and publications cited in this paper [1 – 6]. A genome includes all of the hereditary instructions for creating and sustaining life, as well as instructions for reproduction. The knowledge is encoded in the form of genes [13] and the genes act by encoding information to build a protein, and the "protein actualizes the form and function of the organism." These functions include gene regulation, replication and recombination which are the functional building blocks for the autopoietic behaviors. About 20,000 genes in a human body are present in every cell. There are about 250 different types of cells, each with a characteristic structure and function and each contains a different subset of the 100,000 or so proteins. The knowledge contains the various structures, their relationships and behaviors that are exhibited when a cell is activated, such as where to migrate, and how to evolve in time while interacting with the environment. In essence, the cell evolution processes are dictated by the interaction of genes with each other and with multiple levels of the environment. The regulatory processes are activated by signaling molecules or proteins. The structure and function are subject to change by communication of information about changes in the state of the system.

While the autopoietic processes build, and manage the functions and structure, the cognitive processes are designed to sense, monitor and manage the fluctuations in the system's state and maintain stability using the autopoietic processes. Genes and neuronal networks act as information processing structures exploiting physical and chemical processes in organism's internal and external interactions. Sentience, resilience and intelligence of the organism stem from the information processing structures. Knowledge representation of both the "self" and the environment is encapsulated in the form of a network of networks. Knowledge acquisition and processing through the senses using semi-autonomous cortical columns provide the input for autopoietic and cognitive behavior. Deep reasoning involving predictive analytics and what if simulations are used to manage risk/reward behaviors based on deep memory and experience history.

III. Current State of the Art of Digital Information Processing Systems

While the general purpose computer based on the stored program control implementation of the Turing machines has provided great advances in how we process information and use it to connect people, things and businesses, there are two new drivers that are testing the boundaries of Church-Turing thesis:

1. Current business services demand non-stop operation and their performance adjusted in real-time to meet rapid fluctuations in service demand or available resources. The speed with which the quality of service has to be adjusted to meet the demand is becoming faster than the time it takes to orchestrate the myriad

infrastructure components (such as virtual machine (VM) images, network plumbing, application configurations, middleware etc.) distributed across multiple geographies and owned by different providers. It takes time and effort to reconfigure distributed plumbing which results in increased cost and complexity. Church-Turing thesis boundaries are challenged when rapid non-deterministic fluctuations drive the demand for resource readjustment in real-time without interrupting the service transactions in progress.

2. Current business processes and their automaton assume trusted relationships between the participants in various transactions. Information processing and communication structures assume "trusted relationships between their components. Unfortunately, global connectivity and non-deterministic fluctuations in the participants and information processing structures make it necessary to verify the trust before completing transactions. In order to assure trust, application security has to become self-regulating and tolerant to manage "weak" or "no" trust in the participating entities whether they are other service components, or people or devices. The solution requires decoupling of service security mechanisms (authentication, authorization and accounting) from myriad infrastructure and service provider security operations.

Turing machine implementations of information processing structures as Gödel [14, 15] proved suffer from incompleteness and recursive self-reference not moored to external reality and therefore require external agents to instruct them and judge their outputs [16, 17]. Cockshott et al., [18] conclude their book "The key property of general-purpose computer is that they are general purpose. We can use them to deterministically model any physical system, of which they are not themselves a part, to an arbitrary degree of accuracy. Their logical limits arise when we try to get them to model a part of the world that includes themselves."

The DIME network architecture (DNA) introduced in WETICE 2010 has been well described in the literature (cf., for example, Morana and Mikkilineni, 2011 [19]), while its implementation for providing distributed application management and assuring availability, performance and security is described in a paper in WETICE 2016 [20]. It is important to note that DNA implements sentience and resilience that cannot be accomplished today with the current state of art of cloud computing. A video link demonstrating the sentient nature of distributed web application with auto-scaling, auto-failover and application component mobility in a multi-cloud is given in [21]. The video demonstrates its differentiation from existing state of the art in providing application workload mobility across a heterogeneous multi-cloud deployments.

Artificial intelligence techniques on the other hand, provide deep learning models which do not require algorithms to specify what to do with the data *à la* Church-Turing thesis. Extraordinary amount of data we as humans, collect and consume — is fed to deep learning algorithms implemented in the digital neurons. An artificial neural network takes some input data, and transforms this input data by calculating a weighted sum over the inputs and applies a non-linear function to this transformation to calculate an intermediate state. The three steps above constitute what is known as a layer, and the transformative function is often referred to as a unit. The intermediate states—often termed features—are used as the input into another layer. Through repetition of these steps, the artificial neural network learns multiple layers of non-linear features, which it then combines in a final layer to create a prediction. The neural network learns by generating an error signal that measures the difference between the predictions of the network and the desired values and then using this error signal to change the weights (or parameters) so that predictions get more accurate.

Therein lies the limitation of Deep Learning. While we gain insights about hidden correlations, extract features and distinguish categories, we lack transparency of reasoning behind these conclusions. Most importantly there is the absence of common sense. Deep learning models might be the best at perceiving patterns. Yet they cannot comprehend what the patterns mean, and lack the ability to model their behaviors and reason about them.

True intelligence involves generalizations from observations, creating models, deriving new insights from the models through reasoning. In addition, human intelligence also creates history and uses past experience in making the decision.

Based on our knowledge of how natural intelligence works, we can surmise that the following key elements of human mind, which leverage the brain and the body at cellular level, are missing in current state of the art A.I.:

1. Time Dependence & History of Events: In Nature, systems are continuously evolving and interacting with each other. Sentient systems (with the capacity to feel, perceive or experience) evolve using a non-Markovian process, where the conditional probability of a future state depends on not only the present state but also on its prior state history. Digital systems, to evolve to be sentient and mimic human intelligence, must include time dependence and history in their process dynamics.

2. Knowledge Composition and Transfer Learning: The main outcome of this ability is to understand and consequently predict behaviors by a succession of causal deductions supplementing correlated inductions.

3. Exploration vs. Exploitation dilemma: Creativity and expertise are the consequences of our ability to swap from the comfort zone to unchartered territories and it's a direct and key usage of our transfer learning skill. Analogies and Translations are powerful tools of creativity using knowledge in a domain and applying it in another.

4. Hierarchical structures: As proved by Gödel, an object can only be described (and managed) by an object of a higher class. A key principle of how cells are working by exchanging proteins whose numbers, functions, and

messages are supervised by DNA at cell level or group (higher) level.

In this paper, we address how to integrate sentience and resilience with Deep Learning and introduce Deep Reasoning based on Deep Knowledge and Deep Memory.

IV. INFORMATION PROCESSING AND GOING BEYOND SYMBOLIC AND NEURAL NETWORK COMPUTING STRUCTURES

In order to go beyond Deep Learning, we take the cue from the neocortex in the human brain. The neocortex plays a crucial role in the control of higher perceptual processes, cognitive functions, and intelligent behavior. It acts as higher-level information processing mechanism that uses re-composable neural subnetworks to create a hierarchical information processing system with predictive and proactive analytics. In other words, it allows us to learn, abstract, adapt and create new modes of behavior.

There are hierarchical computing structures that go beyond neural networks to provide models of the observations, abstractions and generalizations from experience and time and history to provide reasoning and predictive behaviors. The models comprising of deep knowledge are designed to capture not only classification of objects, their attributes and relationships but also behaviors associated with them. These behaviors captured as generalizations from history and observations. At any point of time, any new event triggers an evolution of the current state to a future state based on not only the current state but also from its past history.

The non-Markovian behavior gives rise to a new level of intelligence that goes beyond mere computing, communication and cognition alone support. In order to model this level of intelligence, we propose [11] a superrecursive neural network, an ontology based model of the domain of interest created from various pieces of knowledge (observations, experience, science, common sense etc.) and memory that captures time and history of various instances populating the model. Figure 1 shows our proposal for the path to strong AI whose goal is to develop artificial intelligence to the point where the machine's intellectual capability is functionally equal to a human's.

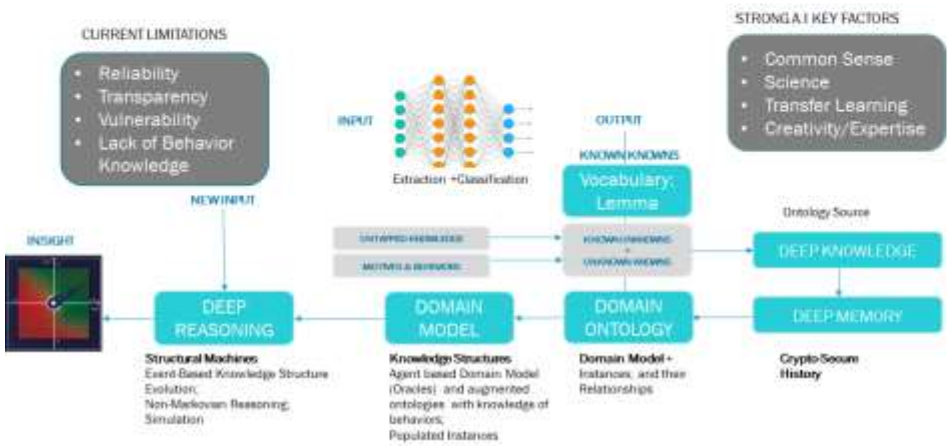

Figure 1: Augmenting Deep Learning with Deepp Knowledge, Deep Memory, Deep Reasoning and Predictive Modeling.

V. TRIADIC AUTOMATA AND AUTOPOIETIC MACHINES

According to Mark Burgin [9, 10] "there is no knowledge per se but we always have knowledge about something. In other words, knowledge always involves some object." Objects are distinguished by their "names." A name may be a label, number, idea, text, and even another object of a relevant nature. In addition to its name, it has other properties. A detailed discussion of named sets, knowledge structures, theory of oracles and structural machines used in this approach are presented in [21 - 24].

The long and short of the theory of knowledge is that objects, their attributes in the form of data and the intrinsic and ascribed knowledge of these objects in the form of algorithms and processes makeup the foundational blocks for information processing. Information processing structures utilize knowledge in the form of algorithms and processes that transform one state (determined by a set of data) of the object to another with a specific intent. Information structures and their evolution using knowledge and data determine the flow of information. Living organisms have found a way to not only define the knowledge about the physical objects but also to create information processing structures that assist them in executing state changes.

The structural machine framework [9, 23, 24] describes a process which allows information processing through transformation of knowledge structures. It involves a control device that configures, executes information processing operations on knowledge structures and manages the operations throughout its life-cycle using a processor. The processor uses the knowledge structures as input and delivers the processed information as knowledge structures in the output space.

VI. Design of an Autopoietic Machine

Autopoietic machines are built using the knowledge network which consists of knowledge nodes and information sharing links with other knowledge nodes. The knowledge nodes that are wired together fire together to manage the behavioral changes in the system. Each knowledge node contains hardware, software and "*infware*[1] " that manages the information processing and communication structures within the node. There are three types of knowledge nodes depending on the nature of the infware:

- Autopoietic Functional Node (AFN): Provides autopoietic component information processing services. Each node executes a set of specific functions based on the inputs and provides outputs that other knowledge nodes utilize.
- Autopoietic Network Node (ANN): Provides operations on a set of knowledge nodes to configure, monitor and manage their behaviors based on the group level objectives.
- Digital Genome Node (DGN): A system-level node that configures a set of autopoietic sub-networks, monitors them and manages them based on system-level objectives

Figure 2 shows our design of an autopoietic machine implementation using existing software IaaS and PaaS infrastructures along with application workloads.

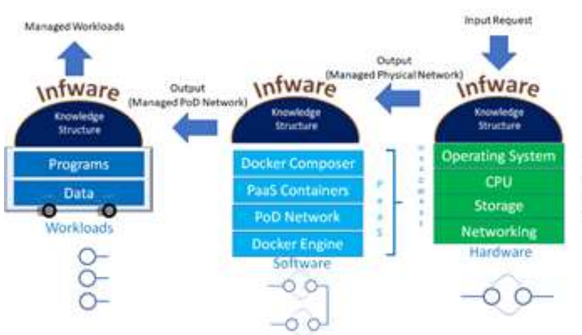

Figure 2: Infware models and manages downstream IaaS, PaaS and workloads

Each knowledge node is specialized with its infware defining the knowledge structures which model downstream entities/objects, their relationships and behaviors which are executed using appropriate software, and hardware. The infware contains the knowledge to obtain resources, configure, execute, monitor and manage the downstream components based on the node level objectives.

[1] The *infware* of a system consists of diverse information specifying how to discover, configure, monitor and manage the hardware, software and other infware to maintain their state evolution based on externally infused knowledge such as business requirements dealing with system availability, performance, security, privacy and regulatory compliance.

Figure 3 shows the design of a knowledge network. Each node uses knowledge structures that manage downstream application workloads deployed using current IT practices. The infware provides the knowledge to model and manage downstream software and hardware structures.

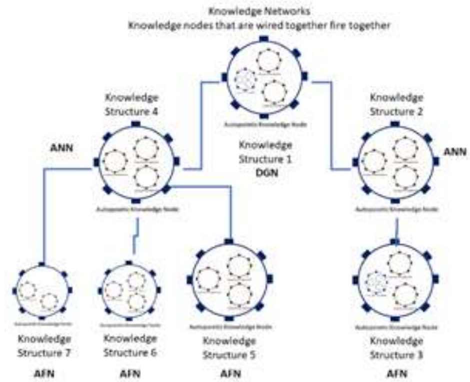

Figure 3: A Knowledge network deployment using the autopoietic machine.

We are currently applying the framework of knowledge networks to model, deploy and manage the life-cycle of a software application with a new degree of sentience, resilience and intelligence. The implementation and the results will be published in a separate paper.

VII. Conclusion

We have presented a new framework to design and implement digital information processing structures to go beyond Church-Turing thesis limitation arising out of resource fluctuations and augment neural network-based Deep Learning with model-based Deep Reasoning. While the theory is sound, based on a mathematical framework, implementations are just beginning and preliminary results sound very promising. A more detailed publication is in preparation with an implementation that combines sentient and resilient implementation of digital autopoietic machines with Deep Reasoning cognizing agents.

While there are few theories about information processing[2] structures dealing with autopoiesis and cognitive behaviors in living organisms, our approach on applying the mathematical tools that define autopoietic machines is unique. Applying the global theory of information and the mathematical tools provided by Prof. Mark Burgin, we propose the knowledge networks to not only explain how to model the genome but also to specify a digital genome that pushes the digital automata to go beyond current half-brained artificial intelligence (which only models the neural network-based behaviors) and the Church Turing thesis (limited in addressing large fluctuations in resource availability or demand). It has not escaped our notice that the knowledge networks and the design and

[2] We refer the reader to a recent review to be presented in the conference on Theoretical and Foundational Problems (TFP) in Information Studies.

(https://tfpiscom.files.wordpress.com/2021/07/bach.pdf) implementation of the digital genome we have articulated here would enable building self-replicating autonomous systems which are more resilient, efficient and intelligent than what is possible with the current state of the art. However, the infused autopoietic and cognitive behaviors fall short in their ability to self-learn and evolve the system by changing the digital genome by themselves as natural living organisms do through natural selection process. At least for, now.

ACKNOWLEDGMENT

One of the Authors (RM) wishes to express his deep gratitude to Late Professor Peter Wegner who influenced the understanding of post-Turing computing models. His personal interactions and guidance both at the Turing Centenary Conference in Manchester in 2012 and ASDS 2015 - International Workshop on Architecting Self-Managing Distributed Systems have influenced this work. The author also wishes to acknowledge many discussions with Prof. Mark Burgin, Eugene Eberbach, Gordana Dodig Crnkovic and Didier Renard from Verablock who shaped the theory behind the new computing models.

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