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# Computation with Democracy: An intelligent System

Kamalika Bhattacharjee<sup>1</sup> and Sukanta Das<sup>2\*</sup>

<sup>1</sup> Department of Computer Science and Engineering, National Institute of Technology, Tiruchirappalli, Tamilnadu, 620015, India

[kamalika.it@gmail.com](mailto:kamalika.it@gmail.com)

<sup>2</sup> Department of Information Technology, Indian Institute of Engineering Science and Technology, Shibpur, Howrah, West Bengal, 711103, India

[sukanta@it.iiests.ac.in](mailto:sukanta@it.iiests.ac.in)

**Abstract.** The notion of artificial intelligence is primarily centered around a *functional approach* where it is tested whether the machine *acts* intelligently. This paper reports a work-in-progress where we advocate for the idea of the machine itself *being* inherently intelligent by incorporating two features in the machine – feature of the life and feature of a democratic system. The first property of the life is *self-replication*, where the machine can reproduce itself indefinitely. The second is *self-organization* which gives the machine ability to reorganize and heal itself. *Fault-tolerance* is another important property of an intelligent system that helps it to achieve reliability and context-sensitive nature. Only a *many-body system* where the elements, like a democratic system, work collectively by interacting among themselves can achieve these properties. Such a machine can be *computationally universal*. Hence, we claim that, a *democratic* model of computation can be a *better* choice for an intelligent system.

**Keywords:** Functional Approach, Self-replication, Self-organization, Fault-tolerance, Computational Universality, Democracy, Cellular Automata(CAs)

## I Introduction

The history of artificial intelligence (AI) is at least as old as the history of computing. One of the significant measures of testing whether a machine is *intelligent* is Turing Test (TT), a behavioral test introduced by Alan Turing in 1950 [27]. In TT, a machine is judged based on its response to some set of questions and passing TT indicates that the machine *shows* intelligent behavior. According to Turing, such a machine should be declared as a thinking machine. Nevertheless, this test is based on a *functional approach* where the machine is declared intelligent if it is successful in performing some functions – in other words, *acts* intelligently. But it does not matter to this approach if or not the system is inherently intelligent like a living organism. One can see the famous *Chinese Room Argument* [25] which differentiates between what *is* intelligent and

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\* Corresponding author

what *acts* intelligently. In fact, the concept of *strong AI* is developed to address this issue [14]. In this work, we want to advocate for the idea of machines which *are* intelligent by going beyond this functional approach.

The formal notion of computing is attributed to Alan Turing and Alonzo Church and is now primarily associated with Turing Machines (TM) [28]. Turing Machine is an abstract model of computation where a finite controller works on an infinite input/output tape based on some predefined rules and computes the output. The modern computer architecture is derived from this model of computation and it is inherently the heart of all machines and artifacts designed to show any kind of intelligent behavior. Obviously, this model is an *autocratic* model of computation. Here, by an autocratic model, we indicate a system where every component is controlled by one or few special components having the supreme authority; so, those components do not have any role in the decision executed by the system and have no independence. Conversely, alternative models of computation have also been proposed, the popular examples of which are Artificial Neural Network (ANN) [21] and Cellular Automata (CAs) [4]. These models may be called as *democratic* as they are composed of many components which enjoy some independence and can interact with each other to make their own decisions. However, these individual decisions can impact the final decision of the system as the system acts on the collective decision or consensus taken by the whole system. In the pioneering work of Langton on *Artificial Life* [16, 17], he has categorically used this class of models in general, and cellular automata in particular. Can such a democratic system be more *intelligent* than an autocratic system? This work targets to give an affirmative answer to this question.

We claim that, any *living* element in nature is more *intelligent* than a non-living element. Therefore, the paramount criterion of an intelligent system is that it has to emulate a living element. However, the preliminary sign of life is that it can *replicate* itself. That is, it can create copies of itself which inherit all its characteristics. If we look into any living element, starting with even a cell at the microscopic level, it can replicate itself. Because of this self-replication, any species *survives* in the evolution – its characteristics are not lost. So, the first property of our proposed system is *self-replication*.

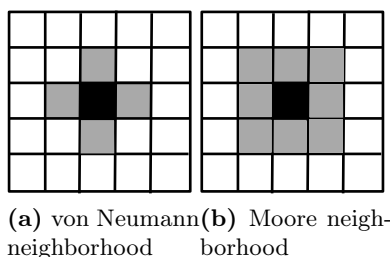
The other two important signs of life are *self-organization* and *self-resilience/fault-tolerance*. This indicates the ability to work correctly even if some part of the system is damaged, repair or heals oneself automatically and upgrade oneself according to the demand of the environment. Due to this fault-tolerance and self-organization capabilities, the *fittest* species have survived in evolution. These features also indicate the re-evaluation and continuous learning process which provide an intelligent species the ability to make *correct* decisions and not to repeat the same mistake. Therefore, the next properties required by our system to be intelligent are self-organization and fault-tolerance .

However, a system that satisfies the above mentioned necessary properties of being intelligent, is inherently a *many-body system* where all entities act together and all decisions are taken collectively. This many-body system can be an ideal choice to model the intelligence in human society as well as the physiological

and natural systems. To find an analogy, we can look at the neuron structure of the human brain which is a perfect example of a many-body system working on a network. Each of these entities of a many-body system can do some amount of work on their own, and can be *non-homogeneous* in nature, that is, they may have diversity in behavior, property and structure, but as a whole the system runs on the result of their collective effort. A decision is taken when all elements of the system come to a *text* consensus. In case of society also, democracy talks about unity and consensus allowing individuals to maintain their diversity and independence. One may find several instances in our lives where to come to a conclusion about any crucial task collective decision is taken. Think for example of a medical board, or a review committee. Here, the collective decision is more reliable and dependable which as a whole makes the system more intelligent. These examples indicate that a many-body system is more reliable than any autocratic system where instead of a single entity, every element has worked together for consensus. So, even if some of the elements are at fault, the system can show resilience to that fault and work correctly. That is, the system is also more available. Similarly, if each of the elements individually decides according to an interaction with its neighboring elements, whereas, the system works only on the collective decision, then this system becomes more sensitive to the context and environment. So, such a many-body system with self-organization and self-replication properties can be an ideal choice for designing intelligent systems. In the next sections, we briefly survey these three necessary properties of an intelligent system – self-reproduction, self-organization and fault-tolerance, which are, in some way, overlapping and related to each other.

## II Self-Replication

The journey of self-replicating machines was initiated by John von Neumann and Stanislaw Ulam [30]. Von Neumann was looking for the logical organization sufficient for a non-trivial self-reproduction. His idea was to abstract the logical form from the natural self-reproduction problem: if self-reproduction can be performed by machine whose behavior can be described as an algorithm, then there exists a Turing machine which can exhibit the same algorithm. So, in turn, a Turing machine exists which could demonstrate its own replication. This idea gave birth to a new mathematical model of computation, named *cellular automata*. A cellular automaton (CA) is a discrete dynamical system comprising of an orderly network of cells, where each cell is a finite state automaton. The next state of the cells are decided by the states of their neighboring cells following a local update *rule*. The snapshot of states of all cells at any time instant is called a *configuration*. Hence, the behavior of a CA is represented by its *global transition function* by which the CA hops from one configuration to another. The beauty of a CA is, it works on very simple rules on a well-define lattice and can be characterized easily, but the simple local interaction and computation of cells result in a huge complex behavior when the cells act together.

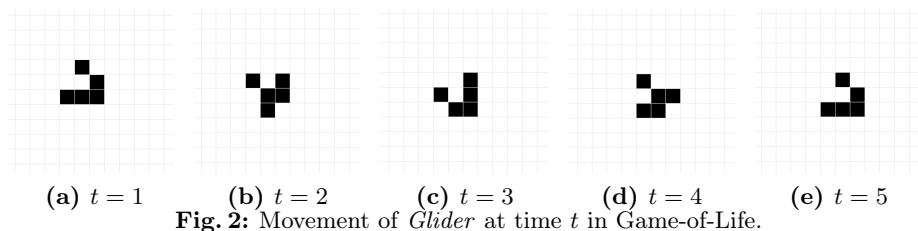


**Fig. 1:** Neighborhood dependencies for 2-dimensional CAs. The black cell is the cell under consideration, and its neighbors are the shaded cells and the black cell itself

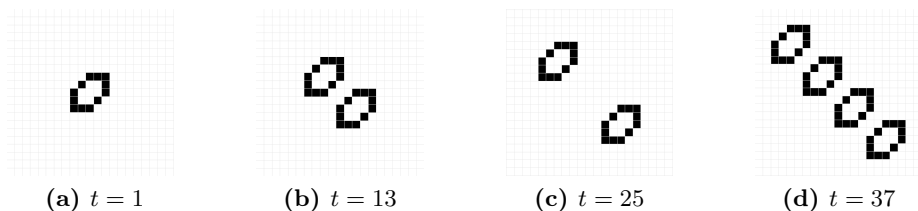
John von Neumann's CA is an infinite 2-dimensional square grid, where each square box, called cell, can be in any of the possible 29 states. The next state of each cell depends on the state of itself and its four orthogonal neighbors (see Figure 1a). This CA can not only model biological self-reproduction, but is also computationally universal. In fact, his machine, an *universal constructor* can construct any machine described on its input tape along with a copy of the input tape attached to the constructed machine. So, self-reproduction happens when the description of the universal constructor itself is given as input, which will keep on reproducing a copy of itself along with its own description indefinitely [16]. It was a path-breaking research showing a existence of a model which is not only powerful enough to reproduce itself (and thus maintain that level of complexity) but also initiate a process of indefinite growth in complexity. Since then, it has been an area of research with a target to reduce complexity and size of the self-reproducing configuration keeping the system computationally universal, see [3, 4, 13, 23] for some related survey. In fact, the research field of *Artificial Life*, a term coined by Christopher Langton [17], was introduced as a descendant of von Neumann's seminal work and is closely related with the field of AI.

Cellular automata have also been utilized to design the famous *Game of Life*, a CA introduced by John Conway and popularized by Martin Gardner [9], where replication and transformation of moving entities can be observed just like in real life (see Figure 2). In Conway's Game of Life, the local rule is  $f : \{0, 1\}^9 \rightarrow \{0, 1\}$ , where state 0 represents a dead cell and state 1 represents an alive cell and the neighborhoods dependency is like Figure 1b (which was proposed by [22]). The rules of the game are very simple [19]:

- Birth: a cell that is dead at time  $t$ , will be alive at time  $t + 1$ , if exactly 3 of its eight neighbors were alive at time  $t$ .
- Death: a cell can die by:
  - Overcrowding: if a cell is alive at time  $t$  and 4 or more of its neighbors are also alive at time  $t$ , the cell will be dead at time  $t + 1$ .
  - Exposure: If a live cell at time  $t$  has only 1 live neighbor or no live neighbors, it will be dead at time  $t + 1$ .
- Survival: a cell survives from time  $t$  to time  $t + 1$  if and only if 2 or 3 of its neighbors are alive at time  $t$ .



However, this simple cellular automaton exhibits a number of powerful phenomena, such as (1) self-reproduction and self-organization, (2) growth of bacterial colony, (3) computational universality, etc. Figure 2 shows an example behavior of Game-of-Life CA where the initial pattern at  $t=0$  is a glider. It is similar to movement of a living body to another location. Figure 3 shows an example of self-replicating behavior by Game-of-Life. Here, the initial pattern is replicated to generate two images after 12 iterations and four images after 36 iterations. For some online resources on the beautiful life-like patterns formed by it, one can



see [1]. Garden-of-Life proves that although individually the cells can have very limited computational ability, but when all the cells work collectively, they are as powerful as the universal Turing machine and can create copies of itself. In this way, the cells with limited computational ability can appear to us *intelligent* when they act together. This shows the power of collective intelligence which can keep on running without human intervention. This work, in fact, motivated a range of researchers around the globe to think of a Life-like intelligent system for various purposes. Like other CAs, the signature property of this Game-of-Life is that it is a decentralized system, as it has no centralized control mechanisms and works collectively to achieve a common goal. These systems have similarities with the notion of democracy. It is accepted in the history of human civilization that a democratic society is more advanced than others. We believe that a computing system can perform in a better way if the laws of democracy are followed by the system.

### III Self-Organization and Artificial Life

Cellular Automata (CAs) have been explored since the 1950s to model biological phenomena such as self-reproduction, sociological phenomena such as growth of a colony, etc. Later, the idea of Artificial Life has been introduced in the domain of

Artificial Intelligence (AI) by further exploring the cellular automata. It has been dreamt by researchers like Christopher Langton [17] that artificial and intelligent life would be created around the principle of CAs. Langton argued that there is a possibility that life could emerge from the interaction of inanimate artificial molecules [16,17]. This molecular logic of life is a dynamic distributed logic. To model this logic, a machine needs to satisfy the following properties. First, it must support massive parallelism - they must have huge computing elements in order to provide for the simultaneous interactions of many operators. Second, the computing elements need only to be locally connected. Third, the machine must support the motion of operators through the field of processing elements. Cellular automata provide the logical universes within which these artificial molecules can be embedded. This initiated the field of Artificial Life (ALife) which has since emerged through the interaction of Biology and Computer Science, but also with important contributions from Physics, Mathematics, Cognitive Science and Philosophy.

Artificial life is the study of artificial systems that exhibit behavior characteristic of natural living systems. This includes computer simulations, biological and chemical experiments, and purely theoretical endeavors. The ultimate goal is to extract the logical form of living systems [17]. It was introduced as a direct lineal descendant and inheritor of von Neumann's seminal research programme, begun in the late 1940s, combining "automata theory" with problems of biological self-organization, self-reproduction, and the evolution of complexity [5, 7, 31]. The question of "what is life?" and its possible answers are the fundamental query in artificial life which expects to underpin the scope, problems, methods, and results in terms of its investigations [3, 23]. Discovering how to make such self-reproducing patterns more robust so that they can evolve to increasingly more complex states is probably the central problem in the study of artificial life. Artificial life has also inherited some roots from AI, particularly that differentiates between "weak" and "strong" AIs, a notion associated with the philosopher John Searle [25]. An analogous distinction can be drawn within artificial life itself, between merely simulating and actually realizing "real" life [18]. Many researchers from diverse backgrounds share the ALife approach and apply it in their own discipline. They seek to understand, through synthetic experiments, the organizational principles underlying the dynamics of living organisms. Then, these principles are used for synthesizing models or artificial systems with lifelike properties [13]. For example, artificial life research is carried out in the computational world working with real chemical systems [20], systems biology [32], synthetic biology [24], epistemological modelling [6]. Thus, integration of self-reproducing programs with self-organization, self-maintenance and individuation (autopoiesis), and the demonstration of sustained evolutionary growth of complexity in a purely virtual world remains the key "grand challenge" problem in the field of artificial life [10].

Several other interesting results on the learning, self-organization, and associative memory problems have also been reported in the literature [2, 17, 31]. One of the important problems here is to organize a reliable system utilizing unreli-

able elements - as in the case of the brain, thousands of neurons die out every day and an individual neuron is not reliable, but the behavior of the brain is relatively stable and reliable. Therefore, the study of this field targets to develop new powerful methods in the field of information processing that can correct or detect any errors [12]. Cellular automata can be regarded as one of the simple mathematical models for the neural networks in the brain. Fault-tolerant cellular automata (FCA) belong to this larger category of reliable computing devices built from unreliable components, in which the error probability of the individual components is not required to decrease as the size of the device increases. In such a model it is essential that the faults are assumed to be transient: they change the local state but not the local transition function. Such a machine has to use massive parallelism, as well as, a self-correction mechanism is to be built into each part of it. In cellular automata, it has to be a property of the transition function of the cells. Due to the homogeneity of cellular automata, since large groups of errors can destroy large parts of any kind of structure, “self-stabilization” techniques are introduced in conjunction with traditional error-correction [8].

#### IV Fault Tolerance and Distributed System

Another class of many-body systems is *distributed systems*, defined as a collection of autonomous independent processing components which interact with each other via an interconnecting communication link to achieve a common goal [26]. A distributed system has to be fault-tolerant – it should be able to continue functioning in the presence of faults. Fault tolerance is related to dependability that includes availability, reliability, safety and maintainability. These features are related; a highly maintainable system shows a high degree of availability, which in turn means that the system will be reliable and fault-tolerant. Ethernet is the first widespread implementation of distributed system, whereas, *ARPANET* is one of the first large-scale distributed system. Success of ARPANET eventually leads to the *Internet* and *World Wide Web (www)*, the most successful example of the power and potential of distributed systems.

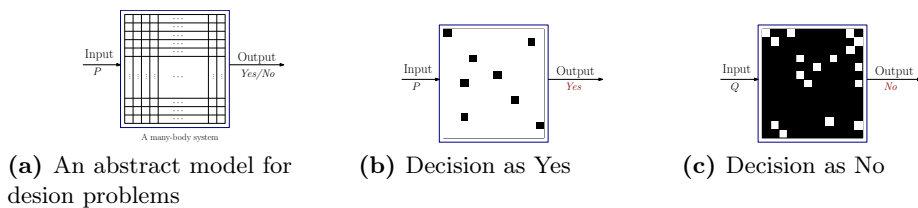
Research has been done to design distributed systems which can detect and repair its faults automatically without effecting its availability. Some of the proposed methods are incorporating redundancy [29], allowing *graceful degradation* [11] etc. However, to work even if some parts of the system break down, the system has to come to a consensus. Moreover, there are several types of faults that the system has to deal with, like – *crash failure*, *omission failure*, *value failure*, *timing failure*, *state transition failure* and *arbitrary failure* [26]. Among them, arbitrary failure, also known as *Byzantine failure* is considered as the most general and most difficult class of failures. In case of Byzantine failure, some of the components may behave arbitrarily, but there is imperfect information on whether a component has failed. The name comes from an allegory of the Byzantine Generals Problem [15] where some of the generals are unreliable (traitors) but to conclude the system has to decide on a consensus. In a Byzantine fault, a component such as a server can inconsistently appear both failed and func-



tioning to failure-detection systems, presenting different symptoms to different observers. So, it is difficult for the other components to declare it failed and shut it out of the network, because they need to first reach a consensus regarding which component has failed in the first place. Therefore, the system has to work knowing some if its components are unreliable, but not knowing which they are. Byzantine fault tolerance (BFT) is the dependability of a distributed system to such conditions. It was shown that, even if one third of the components of a system behave arbitrarily, still the distributed system can work effectively and tolerate the fault [15]. That is, although the system has unreliable components, but if two-third of the components are reliable, the system can intelligently take correct decision *masking* its faults. For other kinds of faults, it is far easier for a distributed system to detect and deal with those faults. This shows the effectiveness of many-body system in handling failures and reliability of such a system in decision making capability. This is the sign of intelligence in a many-body system.

## V To Move Forward

This discussion indicates that a many-body system where the components work together for achieving a common target based on interaction and communication may be more coherent as an intelligent system. Such a system needs to have self-reproducibility, self-organization and fault-tolerance – its universal computation power may follow as a consequence. This system can be resilient to any kind of faults, more available and have self-healing capability. It can also be context-sensitive to the changes in its environment and its decisions can be more reliable as they are taken collectively. Figure 4 shows an abstract diagram for the model. Here, a many-body system is shown which takes any statement as input and gives the decision as ‘Yes’ if the particles of the system reaches to a consensus as yes and ‘No’ otherwise. The *yes* state is shown in *white* and *no* in *black*. Our claim is, such a *democratic* model of computation can be a better choice for an intelligent system than an autocratic one. However, what we need here is a metric to measure the intelligence of a machine. We propose to include following parameter in the metric: abilities of self-reproduction, self-organization, fault-tolerance and capabilities of following democratic values.



**Fig. 4:** Working of a many-body system

In a CA, both time and space are discrete and the cells are updated in parallel. Similarly, in case of our model also, the elements are individual entities whose movement and behavior is apparently independent of each other. There

are also other features of many-body systems having self-organization and self-reproduction which suggest that this can be modeled efficiently by CA. So we want to exploit the inherent locality, massive parallelism and computational ability of cellular automata to design a many-body system where the components work together for achieving a common target based on interaction and communication and may be more coherent as an intelligent system. Such a system may not be exactly a CA, but will inherit all features of self-organization and self-replication offered by a CA. The future work involves development of a class of many-body systems that can imitate the basic features of living elements and that uses the laws of democracy to make the system intelligent in a classical sense. These intelligent systems can revolutionize the existing era of machine intelligence and help the scientists, researchers as well as industry to reach a new level of AI going beyond the traditional capability of intelligent acts performed by machines. Additionally, the incorporation of the essence of democratic values in the computing model can place the definition of intelligence to a different level.

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