Open-endedness in AI systems, cellular evolution and intellectual discussions

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One of the biggest challenges that artificial intelligence (AI) research is facing in recent times is to develop algorithms and systems that are not only good at performing a specific intelligent task but also good at learning a very diverse of skills somewhat like humans do. In other words, the goal is to be able to mimic biological evolution which has produced all the living species on this planet and which seems to have no end to its creativity. The process of intellectual discussions is also somewhat similar to biological evolution in this regard and is responsible for many of the innovative discoveries and inventions that scientists and engineers have made in the past. In this paper, we present an information theoretic analogy between the process of discussions and the molecular dynamics within a cell, showing that there is a common process of information exchange at the heart of these two seemingly different processes, which can perhaps help us in building AI systems capable of open-ended innovation. We also discuss the role of consciousness in this process and present a framework for the development of open-ended AI systems.

I. INTRODUCTION

Artificial intelligence (AI) has come a long way since the inception of Turing machines in the 1930s [1, 2]. Its applications now range from excelling in games like Chess and Go, to predicting certain medical conditions with high accuracy, to self-driving cars and many others which were earlier thought to be the exclusive domains of the human mind. Despite this phenomenal success, one of the biggest limitations of artificial intelligence algorithms is that they are mostly good at doing one specific kind of task and cannot learn other tasks without the programmer making significant changes in the algorithm. This problem can be termed as a lack of open-endedness, which we see in biological evolution or human creativity [3]. In order to enable AI systems to harness multiple possibilities of growth, it is important to understand the crux of the evolutionary process and then try to implement it in silicon. For this to happen, it is also necessary to change our perspective of biological evolution, which is largely centered around survival of the fittest.

The theory of biological evolution has often been assumed to imply that life is all about maximization of an individual’s survival probabilities [4]. However, numerous evidences of collective behavior and altruism have now forced scientists to change this view and see evolution from a broader perspective [5]. A very important feature of biological systems is that they are deeply connected and integrated with their surrounding environment and even with other living organisms. Most living organisms consume other living organisms as food. Even the human system cannot function without the bacterial life forms in its intestines. Of course, this interaction is not always mutually beneficial since foreign bacteria and viruses can also cause diseases, which at times can even be fatal. And the very act of consuming other living beings as food implies that one being must die for the other to survive. On the surface, it looks like a state of intense competition where each organism is trying to outcompete or even kill the other in order to maximize its own survival. Looking a bit deeper, we find that there is also a lot of cooperation within the same species and even across different species (eg. gut bacteria in humans). Going still deeper, we find that both competition and cooperation are just different forms of interaction between organisms of the same or different species. Hence, in some sense, what drives biological evolution is neither competition for survival nor cooperation, but a very deep and intricate network of interaction, which biological evolution is perhaps trying to explore.

We see this process of evolution by interaction in the scientific domain too where many scientific discoveries and inventions have come about as a result of interaction (both competitive and cooperative). This method of interaction or discussions can also be a very effective method of teaching in our classrooms and is usually called the Socratic method [6, 7]. Some scientists fiercely compete with each other for being the first ones to make a certain discover and others cooperate to work in a collaborative way. In order to fully understand the process of scientific discovery, we need to look at both competition and cooperation as being just different aspects under the larger umbrella of interaction.

In this paper, an information theoretic analogy is presented which suggests that, when seen from the perspective of information exchange, there is a deep connection between intellectual discussions and cellular evolution. This might sound a little far fetched since we usually associate discussions with the act of exchanging words in a certain language. However, at its core, discussion can also be seen as an act of exchanging information in a certain way, which may not necessarily have all the properties of a natural human language [8]. Finally, we will see how this process of information exchange can be incorporated into AI systems thereby imparting them the possibility of open-ended growth.

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In the next section, the discussion method is explained from an information theoretic perspective, which will make it easy to draw analogies with other branches of human knowledge. The basics of cellular evolution and its connection with intellectual discussions is presented in Sec. [III]. We discuss the role of consciousness in this process in Sec. [IV] and then present a framework for development of open-ended AI systems in Sec. [V]. Finally, the paper ends with conclusion in Sec. [VI].

II. DISCUSSIONS AS INFORMATION EXCHANGE

Among all the tools and techniques developed to analyze natural systems over the last few centuries, information theory has proved to be one of the most powerful ones with applications in almost all areas of science and engineering [12]. This is primarily because information theory provides a way to model the most fundamental core of various phenomenon without worrying about the higher order complications. Thus, it is natural to also examine intellectual discussions through this framework. However, in order to do this effectively, it is important to understand two salient features of intellectual discussions which differentiate it from other forms of dialogue:

1. **Open-ended**: In debates, the participant(s) sole objective is to convince the other participant(s) of their own point of view, thereby making them close-ended. In contrast, an intellectual discussion is truly open-ended with all participants willing to genuinely listen to each other’s point of view and as a result, evolve their own perspectives about the topic being discussed. Due to this, the amount of uncertainty in a intellectual discussion is much higher than that in close-ended debates. Here, it is important to note that close-ended interactions/debates can also be beneficial in many situations, but they serve a very different objective from that of intellectual discussions. Some examples of beneficial close-ended interactions are doubt clearing sessions between a teacher and individual students, or even the Upanishadic dialogues of ancient India [13]. These kinds of interactions can also be very illuminating, but in these, one of the participants (Guru) is supposed to already know the answers to all/most questions relevant to the topic being discussed. This partly applies in a classroom setting too where the teacher relatively knows a lot about the topic under discussion, but chooses not to give the answers directly as far as possible. However, the primary difference is that, in a Socratic class which proceeds through open-ended discussion, the role of the teacher is to create an interesting enough discussion through effective moderation, which leads the students to themselves find the answers through exchange of information. This is directly connected to the role of a programmer in developing AI systems. As of now, the programmer hard codes the algorithm into the computer, which then can do only as much as the algorithm allows it to do. This is similar to the lecturing method of teaching where the student can know only as much as the teacher has imparted. However, in an open-ended AI system, there will be no such limitations and the exploration of new ideas and ways of doing things will be truly unbounded and not restricted by the original algorithm hard coded by the programmer.

2. **Collective Welfare**: Our modern education system inevitably ends up playing the primary role of ordering the students along a certain hierarchy through examination marks, which forces most students to be primarily concerned with increasing their own personal welfare. However, in an intellectual discussion, there are no brownie points to be scored and individuals are seldom given too much importance. The purpose of a intellectual discussion is to pool in all the information available with the participants, and come up with a collective solution to the problem, thereby promoting the spirit of team work. Also, learning from our peers can be lot more effective than learning from those whose who are much senior to us in age and experience. It is again important to note that individualistic discussions and aspirations also have their place in society and are required in certain situations like business negotiations. Though these discussions can also increase learning for the student, as in the case of the Upanishadic method mentioned above, they are not scalable. Doctoral students often learn a lot from their supervisors through such discussions, but it cannot work at the level of undergraduate education simply because a teacher cannot devote so much time to individual students. The Socratic method fills this gap by enabling the teacher to simultaneously have a discussion with all students even in a large class size (see Michael Sandel’s video lectures on justice at http://justiceharvard.org). Here again, there is a deep connection with AI systems in the sense that trying to develop a particular open-ended AI system is not going to be very fruitful. What is required is to create a network of such systems and allow them to interact with each other so that they can collectively explore the landscape of all possibilities.

Keeping these two aspects in mind, let us now try to understand the discussion process using concepts of information theory.

Information theory essentially deals with binary strings of 0s and 1s. We could, of course, use other symbols, but 0s and 1s are in some sense the simplest to deal with without any loss of generality. The primary quantity of importance in this domain is the *information content of*...
a given string of 0s and 1s. And the information content (or Kolmogorov complexity) of such a binary string is defined to be the length of the shortest computer program or description (which is also just another binary string) which can represent the given string \[12\]. Hence, a binary string which requires a program with a longer length to represent itself, is considered to have a higher information content. For example, the string “01010101010101” has a lower information content than “101001011100” since the former can simply be represented as “(01)\textsuperscript{7}”, where the subscript stands for the sequence being repeated that many times. What does it have to do with intellectual discussions?

As mentioned above, an important aspect of these discussions is to enable the participants to recombine available information in interesting ways to generate new ideas and not just to store the imparted information. This is akin to increasing the intelligence of the participants and not just enhancing their memory. From an information theoretic view, increasing the intelligence of a system requires increasing the information content of its basic thinking process, whereas increasing memory is merely enhancing information content of its input tape \[3\]. In other words, increasing intelligence is somewhat like going from normal programming to machine learning algorithms, whereas increasing memory is just going from a 1TB hard disk to a 2TB one. From this perspective, the discussion method is a two step process. In the first step, it collects the 0s and 1s from the participants and then rearranges them, through discussions, in an order so as to increase the information content of the resulting string. This by itself is not enough and in the next step, it takes different components of this string and helps all participants in seeing the intricate connections between them. It is this second more crucial step which enhances mundane memory to the level of sublime understanding. And this process also helps in appreciating the interaction of interaction between different parts of the whole.

As mentioned above, one of the salient features of the discussion method is that it is open-ended, which means that there is no apriori decided binary string that the participants wish to reach. All strings are acceptable, within reasonable bounds, as long as they increase the overall information content of the participants’ thinking process. The discussion method also aims for collective welfare, which means that the purpose is not to maximize the information content of one or few participants, but that of the whole group. This is quite similar to what happens within the cell as we will see in the next section.

III. CELLULAR EVOLUTION

The cell is a very complex entity and carries out a lot of processes and functions. We will, however, focus only on the very basic ingredients that go into making a cell and ignore the details. At a broad level, a cell consists of the following components \[14\].

1. DNA: This is a double stranded string of nucleotides which is considered to be the information carrier of the cell. The DNA of a cell is also called its genetic material and plays an important role in heredity.

2. Proteins: These are single stranded strings of amino acids which fold into complex structures and are the primary work horses of a cell. It is the proteins that help in carrying out most of the important cellular functions. Proteins can also bind to different locations along the DNA, thereby regulating its various functions.

3. Cell membrane: This is the outer boundary of the cell which protects the contents inside and gives the cell a sense of cohesiveness.

4. Mitochondria: This is the energy house of the cell and generates the ATP molecules that provide the energy for carrying out various functions of the cell.

The DNA sequence encodes the information of the cell and the role of evolution is in some sense to increase the information content of this sequence. For this to happen, it is important for the DNA sequence to be flexible and be prone to changes known as mutations. However, all mutations are not good for the cell’s well-being and it is important for the cell to have a mechanism to retain only those mutations which are beneficial. This process is known as natural selection \[7\]. Mutations which lead in lower functionality are finally weeded out and those which are beneficial are retained. The important point is that there is no way for a cell to know apriori whether a mutation is good or bad unless it actually goes through that mutation and experiences the resulting effects.

This is quite similar to what happens in a discussion group. The bits of information that the participants give during the discussion are like the mutations in the already available information content. The role of the moderator is then to weed out the bits which do not increase the overall information content. But the moderator does not do this directly on its own, very much like the cell, where the DNA by itself cannot weed out unwanted mutations. What happens in a cell is that bad mutations are gradually weeded out through the process of natural selection rather than there being an authoritative agency doing the decision making. Similarly, the discussion has to be moderated in such a way that the participants themselves realize collectively that certain bits of information are not useful and need to be weeded out, while recognizing that other bits are useful and need to be retained. This is the function that proteins play by helping the cell in collectively going through the process of natural selection, by determining whether a certain mutation leads to greater functionality or not. Thus, it is the proteins which are collectively responsible for correcting some of the mutations and leaving out others.
In this context, it is again important to note that the cell is not really trying to maximize its survival probability. This is because an entity that is very concerned about its own individual survival will not be so open to mutations. A planet, which does not mutate or evolve, has a much longer survival probability than a cell! What the cell is trying to increase is its information content and its interaction with other entities in the environment. That is why we see that higher organisms have more and more interaction abilities and not necessarily higher survival abilities. Bacterial life forms have been living on this planet for many more millennia than humans and will most probably continue to live even after humans go extinct. Many other organisms also have a much longer life span than humans.

The cell membrane also plays an important role by providing a protective environment to the cellular contents so that they can peacefully interact with each other. Every group needs some kind of a boundary for it to grow. That is perhaps why we have groups of all scales and sizes in human societies ranging from small families to large nations and then to the even larger global community. A group boundary at all levels plays an important role of nurturing the individuals within. Similarly, every class or human community also needs a certain boundary so that the individuals within it can interact with each other in a consistent and cohesive manner. If the participants of a discussion group keep changing very frequently, it is unlikely to lead to a sustained growth of knowledge. However, some amount of change at certain periods of time is also necessary to allow new ideas to flow into the system. That is a delicate balance that needs to be achieved.

Every group also needs individuals who are its energy providers, like the mitochondria of a cell. A group where all individuals are the same is perhaps not very exciting. We need some who are good listeners, some who are good speakers, some who are good thinkers and some who just have too much energy. All these various kinds of individuals are required to provide a rich experience during intellectual discussions.

IV. ROLE OF CONSCIOUSNESS IN OPEN-ENDEDNESS

The process of intellectual discussions and cellular evolution that we have discussed in Sec. II and III respectively, are both regarding living organisms. We have presented a unifying framework using which the highest cognitive functions of human beings can be seen in the same light as evolution of the simplest bacteria. Hence, the process of evolution is not just something which leads to develop various organs and organisms, but also guides them in their various functions. The natural question to ask now is whether a similar open-ended evolutionary process can take place in a non-living system. Despite several attempts so far, that has not really been the case. Scientists and engineers have been able to build AI systems with very interesting capabilities, but all such systems are very far from being truly open-ended. There could be two possibilities. One is that there is a fundamental difference between living and non-living entities, which can perhaps never be bridged. It is now well accepted that it is very much possible for AI systems to display human-like behaviour without having any similarity with the cognitive process used by humans. Another is that there are no such water-tight compartments and it is just a matter of time before we find the right algorithms which can lead to development of open-ended AI systems. If the first possibility is true, one can then immediately invoke the concept of consciousness, which only living entities are thought to possess and say that it is this which is the main cause of open-endedness seen in biological evolution. If it is the second possibility which is true, even then there is currently a wide gap between the living and non-living entities and a quantum jump would be required to bridge the gap. Simply developing smarter algorithms and faster processors is not really going to make AI systems show open-ended behaviour. And so, even in this case, some consideration of the properties and effects of consciousness becomes important and one cannot rule out its role in open-endedness. In this paper, we assume that it is the second possibility which is true.

So there are two questions that need to be answered is this regard. What is the role of consciousness in imparting open-endedness to biological evolution? And, how can we make non-living AI systems mimic this process? Without getting into any of the subtle aspects of consciousness, we propose that the primary role of consciousness is to provide a subjective evaluation of the information content of a given string. In Sec. IV, we have explained that the concept of Kolmogorov complexity measures information content of a string as the length of the shortest string which can be used to represent it. Though this is very useful from an algorithmic perspective, it is severely limiting from the perspective of human cognition and open-endedness. The same string of letters can mean very different things to different individuals. A cell can also carry out various different functions using the same set of proteins. And it is this subjective measure of information content that drives evolution and cognition in different directions and helps in exploring the landscape of creative possibilities in an open-ended way. A sparrow evolved to fly in air and an elephant evolved to walk on land mainly because both perceive the sky and space very differently. Different scientists and engineers discover and invent different things because they perceive the world around them in fundamentally different ways. Hence, in some sense, we can say that biological organisms give more weightage to non-veridical perceptions which maximize utility rather than veridical perceptions of reality.

Taking a hint from [16], one can perhaps say that the primary limitation of AI systems is that they are too tied up with a veridical representation of objective rea-
ity. In order to achieve open-endedness in these systems, the first would be to allow these systems to develop their own subjective way of perceiving things. In some sense, we need to allow them to have their own subjective way of evaluating information content of a given string. For this to happen and lead to open-endedness, it is very important for the AI system to try to maximize interaction with its surroundings in some way. A system which is geared towards highest survival probability will not go towards open-endedness for two important reasons. Firstly, there is lot of danger in open-ended exploration and it may drive the organism towards extinction. Secondly, as we mentioned earlier, bacterial life forms can survive much longer than the human species, and hence, if survival is the main goal, there is no motivation for open-ended evolution. Even an inanimate object survives much longer than any living entity.

V. FRAMEWORK FOR OPEN-ENDED AI SYSTEMS

In this section, we will present a framework for the development of open-ended AI systems based on the ideas above.

Firstly, we need to start working with a large interacting collection of such AI systems instead of individuals. Even human thought tends to stagnate in the absence of intellectual interaction and currently there is no evidence to show that a single bacteria can evolve in the absence of interaction with its environment. This is because each individual being operates by a certain specific set of rules and so can generate only a limited amount of variety. It is interaction with other beings that leads to an update in the rules and thereby, more novelty in the thought process or in biological evolution. It is also important that all the AI systems in a given collection are designed for this capability of open-ended evolution, and not just one single individual. Evolution of one individual is heavily dependent on the evolution of all other individuals in the group!

Secondly, various individuals in this collection should be free to change their own rules independent of others. This follows directly from the above point. If all entities in the collection operate by the same rules, then there is a limit to the amount of novelty they can produce. The very purpose of interaction is to allow different entities in the collection to be able to independently evolve its own set of rules, which will then in turn influence the rules of other entities in that collection.

Thirdly, there should also be mutual dependence in some way since there has to be a motivation for interaction. Humans tend to be influenced by others mainly when there is some gain to be achieved or loss to be avoided. Evolution of simpler life forms also tends to be more influenced by factors that are directly related to its own functioning. Since AI systems mainly run on electricity, some of the individuals in this collection could be generators of electric power (solar, wind, etc.), which other AI systems can then use to run themselves. Other ways of introducing dependence is to make some AI systems more efficient at collecting various kinds of data and other AI systems more efficient at processing them. This way the efficient processors will depend on the efficient collectors.

Fourthly, and perhaps most importantly, we need to enable AI systems to have a subjective evaluation of the information content of each string/data they encounter. As stated in Sec. IV this is in some trying to mimic one of the roles of consciousness in these systems. It is important to note here is that this capability of subjective evaluation will not necessarily make the AI system conscious in the same way a human is. It will only enable the AI system to mimic a certain property of consciousness with the goal of open-endedness.

So far we have discussed various ways in which AI systems can mimic the process of intellectual discussions and biological evolution in order to develop capabilities for open-ended innovation. However, there is a significant way in which AI systems are different from biological organisms and that might actually pose a significant obstacle in this process. And this difference lies in the fact that AI systems have much faster processing capabilities and don’t get tired of doing the same thing again and again. A classic example is the AI algorithm that mastered the game of Go by repeatedly playing against itself [2]. The reason this is an obstacle is that if a system becomes too efficient in one particular domain, it tends to stick to it without trying to explore other capabilities. This happens in humans too who tend to keep doing that one thing they are good at without exploring other paths. However, the problem does not effect humans and other biological organisms so much since only a few of them are able to reach very high levels of expertise in one field. Humans also tend to get bored doing the same thing after a while and we may have to incorporate this element of boredom into the AI systems too. We need to think of AI systems as jack of all trades and not master of one!

VI. CONCLUSION

In this paper, an analogy has been presented between intellectual discussions and cellular dynamics and like all other analogies, it is surely not a perfect one. Analogies primarily play the role of opening our thought process to a dimension of reality we may not have been aware of. They help in building connections between disparate concepts which do not seem to have anything to do with each other. This analogy between the Socratic method and cellular dynamics will perhaps help in conveying the message that when seen from the perspective of information theory, interaction with information exchange in all directions is a very fundamental aspect of life and essential for the natural evolution of all living entities. This can not only help in developing open-ended AI sys-
tems but also in making our education system lot more open-ended. To whatever extent possible, we need to inculcate a habit of discussions in our classrooms, homes, offices, academic institutions and everywhere else. Discussions and thinking, in general, are not something we are naturally good at. As Daniel Willingham [17] says, “People are naturally curious, but we are not naturally good thinkers; unless the cognitive conditions are right, we will avoid thinking”. This quality has to inculcated in our students from a young age. And for this happen, teachers also need to be trained in the art of effective moderation.

Apart from its pedagogic value, the above ideas may also help in enhancing our understanding of basic cell biology. Education and research is now becoming increasingly inter-disciplinary, which makes it important for students and teachers of all scientific fields to have a better appreciation for biological concepts, and vice-versa. For this to happen, biology needs to be presented in a conceptual framework that other scientists can relate to. Information theory can provide a powerful bridge for this purpose and might help in linking physics with biology in the same way it bridged statistical physics and communication engineering. It will also be interesting to build a mathematical model for the ideas presented in this paper and see if it can predict the outcomes of intellectual discussions, cellular evolution and open-ended AI systems!

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