Harnessing non-neural intelligence for AI.

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Summary:
The state of the art in Artificial Intelligence (AI) has been inspired by our cortical neural hierarchies, and it is mostly implemented on centralized control systems. However, intelligence is not restricted to neural circuits but is now recognized as a widespread ability distributed across the biosphere, a majority of which lies in non-neural systems dealing with decentralized mechanisms of problem solving. Biological entities without a central nervous system (from single cell organisms, plants, groups of cells, and aneural organisms) are now recognized to have decision-making abilities, goal-directed behavior and routinely solve complex problems. Such non-neural intelligence is seen in, for example, Physarum solving mazes, computing behaviors in plants and fungi, swarm behavior in ants and termites, collective somatic cell behavior, somatic information encoding and processing, as well as in immune intelligence and memory. However, the research area focused on harnessing non-neural intelligence to design artificial intelligence remains largely unexplored and holds the possibility of informing new AI architectures that have the ability to solve much broader problems than those utilizing centralized controllers. Such non-neural AI mechanisms that are distributed and decentralized hold the potential for enabling the development of sustainable, energy efficient, and scalable computational solutions to problems at levels ranging from those of individual cells to ecosystems and biosphere. A major advantage of non-neural AI systems would be that they would not cross into the ethical issues of developing conscious or sentient properties which is one of the major concerns of neural AI systems. In addition to living systems, such non-neural AI mechanisms could also be applied to non-living structures.

Introduction:

You might consider:

- What's the big question? What's the exciting science?

- Human brains and centralized neural systems can solve many problems. However, there are many problems that cannot be implemented on centralized control structures. There are hard questions for human brains or current implementations of AI, based on human intelligence, to solve.
- Current neural network-based AI relies on optimization algorithms to achieve learning, decision making, and problem solving in general. However, these are highly energy intensive, computationally intensive, and biased based on input data. Moreover, they are designed to work in silico only.
- Examples of hard questions:
  - To find large prime numbers to improve data encryption security
  - The travelling salesman problem: "Given a list of cities and the distances between each pair of cities, what is the shortest possible route that visits each city and returns to the origin city?" -> can be solved by amoeba https://link.springer.com/article/10.1007%2Fs11047-013-9401-x
    - this is an inspiration to develop non-neural network-based intelligence
  - Graph coloring: In its simplest form, it is a problem one is to perform the task of coloring the objects in a graph such that no two neighboring objects share a boundary are of the same color;
- Non-neural intelligence is ubiquitous: from somatic cell decision making and collective cell behaviors (e.g. wound healing) to physarum searching for food. The non-neural intelligence thereby can have broad applications for problem solving in various spheres and of various kinds.
- Understanding the basic rules/principles of non-neural intelligence and the biological architecture can permit us to construct a non solid-state computer that can solve difficult problems fast and with energy efficiency
- These non-neural AI systems could have properties of regeneration, unbiased problem solving, scalability, energy efficiency, sustainability, and self-governance without the concern becoming sentient and conscious like the AI designed on neurons and nervous system. This would constitute a paradigm shift for how we define computers, for AI design, and for how AI is deployed as a problem solving tool.

- What's the potential impact?

  -Better knowledge of non-neural intelligence
  -know the biological hardware and software components of non-neural intelligence in nature
  -know the rules and principles of non-neural or distributed intelligence
  - Novel AI designs that are emergent, self-sustaining, regenerating, highly energy efficient, broadly applicable beyond requirement of central processing, and unbiased by input data.
  - solving problems in the vast space and scale/need by decentralized problem solving
  - transcendance of implementation and scale specificity

- Useful applications
    - biological discovery
    - efficient power grid design: minimize regional blackout
    - secure data encryption
    - efficient route design for delivery (UPS, FedEx, etc)
    - efficient design for cell phone tower location distribution: better reception
    - better process to design drugs to treat disease: better understand predict structure-function relation
    - designing sustainable synthetic bio- and ecosystems driven by AI
- Merits of the system
    - robustness, because the computing units are decentralized, maybe self-regenerative
    - adaptive
    - energy efficiency

- Advantage of these non-neural AI systems would be that they are not defined by one problem we are trying to solve. Just like non-neural biological systems can perform decision-making in lots of different conditions and solve a multitude of problems, these non-neural AI system might be able to solve massive range of problems across scale.

- Why now?
    - Brute-force solutions, facilitated by Moore's Law, might not improve solving power for hard questions listed above (see more NP-hard questions)
    - Energy efficiency is a big concern.
    - Rapid environmental change requires rapid responses for adaptation, robustness, and resilience.
    - The era of big data requires new approaches for 'intelligent' and adaptive computing to crunch data, or to mine the data for meaningful interpretation.
    - Non-neural intelligence is now -being discovered to be extensively prevalent across biological systems. These are fantastic decision making computations without the constraints of neural systems. With this knowledge, the time is now ripe to explore and understand these more and use these to design highly novel and broadly applicable non-neural AI systems.

- What are the state-of-the-art technologies, applications, etc ...?
    - Currently neural network-based AI is considered the state of the art. Watson from IBM is one of the most powerful AI computers. However, these are highly biased, highly energy intensive, non-sustaining, highly narrow in applications.
    - Agent-based computational algorithms are inspired by swarm intelligence, and genetic algorithms are procedural adaptations to problem solving *in silico*, ultimately using the same architecture and facing the same constraints neuron network based AI.
    - Bank of visual/graphical representations of non-neural solutions to functions analogous to those accomplished in the cortex is a significant deliverable in its own right.

- Elaborate the key barriers and challenges that will need to be overcome.
  - Scientists may be resistant to including behaviors and processes in non-metazoans a definition of “intelligence”. However there is abundant evidence of decision making, problem solving, and even forms of learning in organisms from bacteria, plants and slime molds. Excluding these organisms from notions of intelligence has limited the toolkits available to bio-inspired computation and AI.
  - It is important to better understand non-neural intelligence in systems such as physarum, stentor, dictyostelium, microbial biofilms, plants, and somatic level decision-making. Goal directed behavior in environments such as developmental biology would be highly informative for understanding the basic principles and rules of these non-neural intelligence. This requires vast resources invested in studying the non-neural intelligence and getting to understand the mechanisms both hardware and software required for execution of this non-neural intelligence, as well as in performing comparative analysis to find basic common rules and principles of this non-neural intelligence.
  - Visual descriptions of non-neural intelligence processes may get around the problem of applying the terminology of centralized cortical control to these phenomena. Visual descriptions can be used as a common “language” more easily translatable into AI architectures.
  - Challenge is: Can we design an AI system based on the non-neural intelligence “hardware” and “software” found in biological systems.
  - It is unknown whether it is feasible to design synthetic systems to mimic these hardware and software properties of non-neural intelligence systems to an extent that they exhibit the self-governing problem solving behavior seen in non-neural intelligence systems in biology, or to directly build a computer using unconventional materials (i.e. cells)?
  - How to implement the concept:
    - both the in silico, as well as in vivo/situ approaches are worth exploring after defining and understanding how intelligence works in a non-neural form. However, given past and current successful implementations of bio-inspired problem solution methods, we want to emphasize the aspect of intelligence implementation (learning, adaptation, complex problem solving) in vivo/situ as a key novelty in our aims.
    - Thus, as an alternative to continue to implement solutions in silico, we would perform the computation in a biological system. Then what is the readout? How do we measure the readout as the “answer” to our computing system.
      - The advantage of constructing the *de novo* computing is that we will be able to encode a desired structure to access a specialized computing “function”, which might enable faster problem solving.

- A clearer, better defined computing task (i.e. benchmark) as the first "checkpoint" to test the new system: is it better? how much better is good enough compared to neural network-based intelligence.
- Where do we find inspiration in addition to Amoeba and swarm? (plants and fungi might be the answer)

- What might be broader impacts?
  - Designing algorithms based on non-neural intelligence computing may eventually lead to AI that is energy efficient, decentralized thereby robust and strong from any deliberate perturbation or stochastic events, and flexibly evolve.
  - Bringing a new paradigm for problem solving.
  - Studying intelligence and decision making in non-neural systems may inform novel training and management architectures.

- How does it reintegrate biology?
  - Requires studying biology within a novel context and from the molecular level to intelligence and decision making level, and from individual organisms to the population and ecosystem level, as well as from computational applications to biological implications.
  - Different scientists from different disciplines will be required to work together to build the non-neural AI.
  - The process will fill the gap of knowledge, jargon, and rationale
  - A solution design at a given scale might successfully solve problems at a different scale.
  - Similarly, implementations might be scalable across organismal levels

- What disciplines might be needed?
  - Non-neural cognition and Liquid Brains
  - Comparative Anatomy
  - Cell and Molecular Biology
  - Biophysics and Structural Biology
  - Physiology and Neuroscience
  - Developmental and Organismal Biology
  - Community and Ecosystems Biology
  - Communications and Information Biology
  - Theoretical Biology - Information theory
  - Systems Biology
  - Computational Biology
  - Applied Math
  - Computer Science
  - Biomaterials and Biofabrication
  - Biological Engineering
  - Soft Matter Physics

- Electric Engineering

- Intended audience of the paper.
    - Scientists from the fields listed above, NSF and other funding agencies.

Useful Feedback:

Positives-

Perhaps combine with physical hypothesis driven models, help generate interpretable models compared to AI black box.
Would help us know what we don't know.
Super-relevant + far reaching problem
Emphasize the difference in problem solving structure.

Concerns-

How to quantify differences between human/ animal cognition + neural dependent neural nets
How does biology (neuroscience) transcend computer science in this domain
How might we create good communication interfaces between ourselves + AI devices - Some work on this from Jeff Heer and Chris He - and even communication between animals, species and ecosystems.
Are there ethical concerns
How to show non-neural AI does not represent a cryptic connectionist model equivalent to neural nets. -> EVG: Even if a solution were to have a neural network representation, qualifying metrics would determine improvement/optimality w.r.t energy efficiency, accuracy, sensitivity, etc. Notice that even in these comparisons we are still bound to current understanding of decision making.
How might you more sharply define what you mean by computation / AI.
How does it integrate with quantum computing or new modeling?
What are the benefits to biology and computational science
What are the limits of non-neural AI?
What are the limits of non-neural systems in nature?

Potential -

- Better define categories of AI for problem applicability
- Could expand and refine the definition of non-neural AI
- The connection with evolution is cool. There is some work (and more should be proposed) on how complex, neural sensor systems evolve using AI.

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