Why Open-Endedness Matters

Kenneth O. Stanley
Uber AI Labs
kstanley@uber.com

Abstract Rather than acting as a review or analysis of the field, this essay focuses squarely on the motivations for investigating open-endedness and the opportunities it opens up. It begins by contemplating the awesome accomplishments of evolution in nature and the profound implications if such a process could be ignited on a computer. Some of the milestones in our understanding so far are then discussed, finally closing by highlighting the grand challenge of formalizing open-endedness as a computational process that can be encoded as an algorithm. The main contribution is to articulate why open-endedness deserves a place alongside artificial intelligence as one of the great computational challenges, and opportunities, of our time.

Keywords
Open-endedness, open-ended evolution, open-ended algorithms, artificial intelligence, machine learning, quality diversity, novelty search

How can we avoid being amazed by the avalanche of miraculous surprises just outside the window? Every blade of grass, the birds pecking at the ground, the trees with their beautiful canopies, the humans casually walking by on a spring day—where in the world did all that unfathomable complexity come from? Who could have predicted it all when there were only giant clumps of particles flinging through the vacuum of space eons in the past?

Surprise seems embedded deep in the core of reality. Our universe endlessly generates things that are wild beyond imagination. Sure, *maybe* you can think of a mystical new creature if you're creative—a unicorn or a Minotaur perhaps—but can you literally build one that truly lives, and a billion other incredible living testaments to astronomical complexity on a single world in a single run? Forget it, it sounds impossible, but here we are, right in the middle of it—we have horses and dolphins and spiders, and all of natural life, all here, all created in one vast explosion of surprise and complexity.

There are many profound questions at the heart of nature, but often such questions elude purely algorithmic explanation. Why does the universe exist? What explains consciousness? What is time? Yet open-endedness is an exception. The existence of a process with the power to conjure continual surprise through epic creativity and boundless increasing complexity, while among the most fascinating hallmarks of the natural world, actually might sit atop an algorithmic explanation. It seems plausible that such a process is ultimately about information and the interaction between different representations subject to lawful rules—the stuff of algorithms.

If that is true, then open-endedness is one of the few great mysteries of our world (perhaps alongside intelligence) that might succumb to complete computational explanation, and even computational implementation. In fact, as with the field of artificial intelligence (which is closely related), for open-endedness explanation and implementation might be one and the same—if we can produce an open-ended algorithm in the most grandiose spirit of open-endedness in nature, then we almost certainly have fundamentally understood it. And with that revelation will come a massive chunk of the explanation of our origin, the origin of intelligence, and billions of other monumental creations of the living world.

The tie between open-endedness and intelligence is similarly tantalizing. If indeed evolution on Earth is an open-ended process, then we as humans and our intellect are ourselves the product of such a process, hinting that open-ended processes themselves may be a fundamental ingredient in

the attainment of intelligence at the human level or beyond. In this way, the most ambitious reaches of artificial intelligence and open-endedness may be inextricably linked.

In fact, humans are an interesting case because we are not only a product of an open-ended process, but we also exhibit our own *non-evolutionary* (strictly speaking) open-ended processes. For example, the history of human invention, innovation, and even art, is fundamentally open-ended. Every invention becomes a stepping stone to more inventions in an ongoing divergent symphony of creation that never ends. That is one reason that those interested in open-ended innovation sometimes study non-evolutionary histories, such as patent filings over the centuries [5]. Not only that, but even the trajectory of a single human lifetime seems often open-ended, beginning with the discovery of walking and talking, and then diverging off across uniquely individual landscapes of ideas and inventions. Open-endedness is not only our creator, but also a deep-seated aspect of our character and creativity. We have much to learn about ourselves in understanding it.

Imagine then the power unleashed if we actually figure out how to implement open-ended algorithms. Unlike algorithms in, for example, machine learning that learn to solve problems we *ask them to solve*, open-ended algorithms could produce surprises beyond our imagination *without the need to ask*. A revolution would sweep across computer-aided design as algorithms churn out endless processions of novel architectures and designs. Routine aspects of our lives, like clothing or furniture, could begin to stir with excitement and novelty. Repertoires of capabilities (as we are starting to see with quality diversity algorithms [10, 21]) could be generated in single runs, yielding not single solutions or controllers, but entire libraries of advanced behaviors. New forms of art and music might burst not only from open-ended algorithms, but from open-ended processes with humans in the loop [33]—yet another branch of this nascent discipline. Video game worlds could unfold with all the richness and surprise of a natural ecology, offering discovery and adventure without end. Even open-ended experiments in vivo might energize a new corner of research in biology. It could even accelerate human innovation through our renewed understanding of how open-ended innovation really works. Perhaps it would even be the key that unlocks the most powerful realizations of artificial intelligence. While these pronouncements risk a tinge of sensationalism, it is worth recalling that an open-ended process is responsible for all of living nature in a single run. The significance of even a fraction of such creative power is hard to overstate.

We have much work remaining. I have avoided here a direct attempt at even an explicit definition of open-endedness, in part because even its definition is in contention [2, 11, 15, 22, 29, 30]. Indeed, open-endedness is likely a matter of degree rather than an either/or proposition, and pinning down its level, while the subject of much effort as well [3, 4], remains a challenge. But my aim here is not to address these challenges; the remaining pages of this issue and this journal make strides in that direction. Rather, sometimes it is worth a moment, especially at the dawn of a new discipline, simply to contemplate its motivation. Artificial intelligence too has incurred its debates on the nature of intelligence, but its revolutionary potential is still completely clear. Open-endedness similarly is a phenomenon of such grandiose implication that it can generate years of heated argument, but its pursuit is no less noble or profoundly impactful for the controversy it inevitably entails.

The field is beginning to coalesce. A history of thought is beginning to crystallize that provides a foundation for a culture of future progress. From its origins in its recognition as a key challenge for artificial life [6], to the early (and more recent [9]) proliferation of "ALife worlds" that aim to find a hint of it in artificial microcosms of nature [8, 19, 23, 34], to new kinds of algorithms (e.g., coevolution [20], novelty search [16], MAP-Elites [18], minimal criterion coevolution [7], and POET [32]) that aim to draw on its power, to early attempts to integrate humans into systems with open-ended properties [14, 24], open-endedness is poised to explode. Indeed, an enormous wellspring of potential is just beginning to stir [1] as the broader machine learning community begins to take notice. Open-endedness is not the exclusive province of any one discipline—it is not confined to evolution, and the intuitions behind many learning algorithms can be put to work in its advancement. This interdisciplinary potential is part of its excitement—it can be a unifier of fields even as it emerges increasingly confidently as a field in its own right.

As I have argued with the help of colleagues elsewhere [26], open-endedness is a grand challenge in the same spirit that artificial intelligence is a grand challenge. It is one of the most profound and beautiful phenomena in nature, a prolific creator without a final purpose. The ultimate explanation for its power, its necessary conditions [12, 13, 17, 25, 27, 28, 31], and how generally it can be implemented or applied, remain a mystery. While we will inevitably disagree on many of its aspects, that should not deter our resolve in its pursuit. Like intelligence, it is a part of our reality even as its essence remains ephemeral to us, which is all the more reason for the next generation of scientific pioneers to set out in its quest. We should expect surprises.

References

1. Balduzzi, D., Garnelo, M., Bachrach, Y., Czarnecki, W. M., Perolat, J., Jaderberg, M., & Graepel, T. (2019). Open-ended learning in symmetric zero-sum games. arXiv preprint arXiv:1901.08106.
2. Banzhaf, W., Baumgaertner, B., Beslon, G., Doursat, R., Foster, J. A., McMullin, B., Veloso de Melo, V., Miconi, T., Spector, L., Stepney, S., & White, R. (2016). Defining and simulating open-ended novelty: Requirements, guidelines, and challenges. *Theory in Biosciences*, *135*(3), 131–161.
3. Bedau, M. A., & Packard, N. H. (1991). Measurement of evolutionary activity, teleology, and life. In C. G. Langton, C. Taylor, J. D. Farmer, & S. Rasmussen (Eds.), *Proceedings of Artificial Life II* (pp. 431–461). Redwood City, CA: Addison-Wesley.
4. Bedau, M. A., Snyder, E., & Packard, N. H. (1998). A classification of longterm evolutionary dynamics. In *Proceedings of Artificial Life VI* (pp. 189–198). Cambridge, MA: MIT Press.
5. Bedau, M. A., Gigliotti, N., Janssen, T., & Kosik, A. (2019). Open-ended technological innovation. *Artificial Life*, *25*(1), 33–49.
6. Bedau, M. A., McCaskill, J. S., Packard, N. H., Rasmussen, S., Adami, C., Green, D. G., Ikegami, T., Kaneko, K., & Ray, T. S. (2000). Open problems in artificial life. *Artificial Life*, *6*, 363–376.
7. Brant, J. C., & Stanley, K. O. (2017). Minimal criterion coevolution: A new approach to open-ended search. In *Proceedings of the Genetic and Evolutionary Computation Conference, GECCO '17* (pp. 67–74). New York: ACM.
8. Channon, A. D., & Damper, R. I. (2000). Towards the evolutionary emergence of increasingly complex advantageous behaviours. *International Journal of Systems Science*, *31*(7), 843–860.
9. Channon, A. (2019). Maximum individual complexity is indefinitely scalable in Geb. *Artificial Life*, *25*(2).
10. Cully, A., Clune, J., Tarapore, D., & Mouret, J.-B. (2015). Robots that can adapt like animals. *Nature*, *521*, 503–507.
11. Dolson, E. L., Vostinar, A. E., Wiser, M. J., & Ofria, C. (2019). The modes toolbox: Measurements of open-ended dynamics in evolving systems. *Artificial Life*, *25*(1), 50–73.
12. Guttenberg, N., Virgo, N., & Penn, A. (2019). On the potential for open-endedness in neural networks. *Artificial Life*, *25*(2), 145–167.
13. Harrington, K., & Pollack, J. (2019). Escalation of memory length in finite populations. *Artificial Life*, *25*(1), 22–32.
14. Hastings, E. J., Guha, R. K., & Stanley, K. O. (2009). Automatic content generation in the galactic arms race video game. *IEEE Transactions on Computational Intelligence and AI in Games*, *1*(4), 245–263.
15. Hintze, A. (2019). Open-endedness for the sake of open-endedness. *Artificial Life*, *25*(2), 198–206.
16. Lehman, J., & Stanley, K. O. (2011). Abandoning objectives: Evolution through the search for novelty alone. *Evolutionary Computation*, *19*(2), 189–223.
17. Moran, N., & Pollack, J. (2019). Evolving complexity in prediction games. *Artificial Life*, *25*(1), 74–91.
18. Mouret, J.-B., & Clune, J. (2015). Illuminating search spaces by mapping elites. ArXiv e-prints, abs/1504.04909.
19. Ofria, C., & Wilke, C. O. (2004). Avida: A software platform for research in computational evolutionary biology. *Artificial Life*, *10*(2), 191–229.
20. Popovici, E., Bucci, A., Wiegand, R. P., & De Jong, E. D. (2012). *Coevolutionary principles* (pp. 987–1033). Berlin, Heidelberg: Springer.

21. Pugh, J. K., Soros, L. B., & Stanley, K. O. (2016). Quality diversity: A new frontier for evolutionary computation. *Frontiers in Robotics and AI*, 3(40).

22. Rasmussen, S., & Sibani, P. (2019). Two modes of evolution: Optimization and expansion. *Artificial Life*, *25*(1), 9–21.

23. Ray, T. S. (1991). An approach to the synthesis of life. In J. D. Farmer, S. Rasmussen, C. Langton, & C. Taylor (Eds.), *Artificial life II* (pp. 371–408). Redwood City, CA: Addison-Wesley.

24. Secretan, J., Beato, N., D'Ambrosio, D. B., Rodriguez, A., Campbell, A., Folsom-Kovarik, J. T., & Stanley, K. O. (2011). Picbreeder: A case study in collaborative evolutionary exploration of design space. *Evolutionary Computation*, *19*(3), 345–371.

25. Soros, L. B., & Stanley, K. O. (2014). Identifying necessary conditions for open-ended evolution through the artificial life world of Chromaria. In *ALIFE 2014: Proceedings of the Fourteenth International Conference on the Synthesis and Simulation of Living Systems* (pp. 793–800). Cambridge, MA: MIT Press.

26. Stanley, K. O., Lehman, J., & Soros, L. (2017). Open-endedness: The last grand challenge you've never heard of. https://www.oreilly.com/ideas.

27. Taylor, T. (2012). Exploring the concept of open-ended evolution. In C. Ofria, C. Adami, D. Bryson, & R. Pennock (Eds.), *Artificial life 13 (proceedings of the Thirteenth International Conference on the Simulation and Synthesis of Living Systems)* (pp. 540–541). Cambridge, MA: MIT Press.

28. Taylor, T. (2015). Requirements for open-ended evolution in natural and artificial systems. *CoRR*, abs/1507.07403.

29. Taylor, T. (2019). Evolutionary innovations and where to find them: Routes to open-ended evolution in natural and artificial systems. *Artificial Life*, *25*(2), 207–224.

30. Taylor, T., Bedau, M., Channon, A., Ackley, D., Banzhaf, W., Beslon, G., Dolson, E., Froese, T., Hickinbotham, S., Ikegami, T., & McMullin, B. (2016). Open-ended evolution: Perspectives from the OEE workshop in York. *Artificial Life*, *22*(3), 408–423.

31. Waddington, C. H. (1969). Paradigm for an evolutionary process. In C. H. Waddington (Ed.), *Towards a theoretical biology*, *Vol. 2* (pp. 106–128). Edinburgh: Edinburgh University Press.

32. Wang, R. Lehman, J., Clune, J. & Stanley, K. O. (2019). Paired open-ended trailblazer (POET): Endlessly generating increasingly complex and diverse learning environments and their solutions. arXiv preprint arXiv:1901.01753.

33. Woolley, B. G., & Stanley, K. O. (2014). A novel human-computer collaboration: Combining novelty search with interactive evolution. In *Proceedings of the 2014 Conference on Genetic and Evolutionary Computation, GECCO '14* (pp. 233–240). New York: ACM.

34. Yaeger, L. (1994). Computational genetics, physiology, metabolism, neural systems, learning, vision, and behavior or poly world: Life in a new context. *Proceedings of the Artificial Life III Conference*, *Vol. 3* (pp. 263–298).