Revision Notes: I reduced the number and length of quotations, and discussed better the quotations I included. Instead of relying on quotation, I tried to carry the argument in my own prose. I paid attention to topic sentences, in order to fortify the organization of my paper. In addition, I developed the parallel between the Tree of Life and the trees of AI search algorithms.

Visualizing Darwin's Theory and its Revolutionary Implication

In all editions of his book *On the Origin of Species*, Charles Darwin included one, and only one, illustration: a taxa chart, which helps in conceptualizing his idea of evolution. Darwin visualized the evolutionary process as a Tree of Life. I will describe Darwin's Tree of Life and show how its features explain the observations made by geologists and taxonomists in Darwin's time. I will then show that Darwin's Tree of Life illustrates the revolutionary idea that design can emerge without a designer but with time, from the mindless processes of descent with modification and natural selection.

Darwin's taxa chart is a diagram in two dimensions showing the evolution of species. The vertical axis represents time, with later times on top of earlier times, the direction of time being the opposite of its direction in the expression "descent with modification". The horizontal axis represents some abstract design space, so that the horizontal distance between two organisms roughly represents their morphological differences. Darwin uses the same diagram to discuss evolution at different resolutions: organisms to varieties, varieties to species, species to genera, genera to families, families to order.

At the finest resolution, each organism would be represented on the chart as a tiny straight vertical line, starting at the time of its birth and extending for the short duration of its life. The tiny line of an organism would be very close in time and space to the lines of its direct ancestors, below, and of its descendants, if any, above. Through descent with modification, as variations accumulate, the tiny lines would horizontally drift from the lines of their ancestors. Through natural selection, some lines would go extinct, leaving no offspring. The living organisms are all at the top of the Tree of Life, being the descendants of generations of organisms that successfully reproduced.

Contemplating the diagram from a lower resolution, organisms of the same variety within a species living at the same time might appear like a dot, being so close together. Their offspring might appear as nearby dots, and so on, until, many thousands generations later, the descendants might appear as dots sufficiently apart to be classified as new varieties. By the same processes at different resolutions, varieties might diverge enough to give rise to sub-species, which might diverge enough to give rise to genera, then families, then even orders, etc. The Tree of Life explains how each variety, specie, genus, each family, and even each order, shares common ancestors in once living organisms:

> "The green and budding twigs may represent existing species; and those produced during each former year may represent the long succession of extinct species. […] The limbs divided into great branches, and these into lesser and lesser branches, were themselves once, when the tree was small, budding twigs; and this connexion of the former and present buds by ramifying branches may well represent the classification of all extinct and living species in groups subordinate to groups."[1]

[1] Darwin, Charles. *On the Origin of Species*. 1st edition. (First published 1859. Cambridge, Mass.: Harvard University Press, 1975.) p. 129

The Tree of Life helps make sense of the observations coming from geology and taxonomy, explaining the intermediate forms in the fossil records, the hierarchical organization of organisms into groups (varieties, species, genera, etc.) and the fuzziness of the notion of species.

The fossil records of a geological period should map to a slice of corresponding time in the Tree of Life. Each species in the Tree of Life is connected to any of its ancestor, by an unbroken downward series of intermediaries. If two species share a common ancestor, their downward series of intermediaries will gradually approach each other until they converge in the common ancestor. Therefore, as Darwin says,

> "those groups, which have within known geological periods undergone much modification, should in the older formations make some slight approach to each other; so that the older members should differ less from each other in some of their characters than do the existing members of the same groups; and this by the concurrent evidence of our best paleontologists seems frequently to be the case."[2]

The hierarchical organization of organisms into varieties, species, genera, families and orders can also be explained by the Tree of Life. Each group maps to a branch of the Tree, rooted in a common ancestor. Members of a group are likely more divergent in character as their common ancestor is older, because changes has had more time to accumulate via the process of descent with modification. The process of natural selection also plays a role in clustering organisms by causing the extinction of intermediary links between two groups.

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[2] Darwin. p. 333

Finally, the gradual emergence of a branch in the Tree of Life justifies Darwin's reluctance to give a sharp definition of the word "species". Indeed, species are expected to have fuzzy boundaries because the process of descent with modification operates at the finest resolution, between parent and offspring. Furthermore, we cannot recognize a speciation event as it happens but only retrospectively. As Daniel Dennett puts it, a speciation event is a "retrospective coronation":

> "There is not *and could not be* anything internal or intrinsic to the individuals – or even to the individuals-as-they-fit-into-their-environment —from which it follows that they were – as they later turn out to be – the founders of a new species. We can imagine, if we want, an extreme (and improbable) case in which a single mutation guarantees reproductive isolation in a single generation, but, of course, whether or not the individual who has that mutation counts as a species-founder or simply as a freak of nature depends on nothing in its individual makeup or biography, but on what happens to subsequent generations – if any – of its offspring."[3]

Again, by viewing the Tree of Life at different resolutions,

> "the same moral applies to the creation of new genera, families, and even kingdoms, of course. The major branching that we would retrospectively crown as the parting of the plants from the animals began as a segregation of two gene pools every bit as inscrutable and unremarkable at the time as any other temporary drifting apart of members of a single population."[4]

In short, a group in the hierarchical organization of organisms (be it a variety, specie, genus, family, order, kingdom, etc.) maps to a branching in the Tree of Life. The branching can only be recognized by looking ahead of the branching (fuzzy) point, into the fate of its descendants: the branching cannot be inferred from the past or present but depends on the future of its branching point.

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[3] Dennett, Daniel. *Darwin's Dangerous Idea*. (New York: Simon & Schuster, 1995.) pp. 99-100
[4] Dennett. p. 100

Darwin's Tree of Life depicts the shape of the evolutionary process, an iterative bottom-up process arising from the principles of descent with modification and natural selection. As such, Darwin's Tree of Life embodies the revolutionary implications of his theory of evolution, not only in the realm of biology but also in the realm of philosophy. I will now discuss a few of these implications: the Tree of Life as a counterexample to the Argument from Design, the Tree of Life as an undermining of Locke's deduction of the primacy of Mind, the Tree of Life as an argument for the possibility of artificial intelligence and consciousness.

The Argument from Design is perhaps the favorite argument of natural theology, which aims to give religious beliefs a scientific basis. It can briefly be stated as:

1. Parts of this world, such as living beings, are too complex to have occurred by accident and must have been designed.
2. Design implies a designer.
3. Therefore, a designer, God, must exist.

William Paley offers the most influential version of this argument in his *Natural Theology*, which Darwin read and enjoyed. Paley introduces the famous analogy of a watch implying a watchmaker. In *Dialogues Concerning Natural Religion*, David Hume's character Cleanthes defends a version of the Argument from Design:

> "The curious adapting of means to ends, throughout all nature, resembles, exactly, though it much exceeds, the productions of human contrivance – of human design, thought, wisdom and intelligence. Since therefore the effects resemble each other, we are led to infer, by all rules of analogy, that the causes also resemble, and that the Author of Nature is somewhat similar to the mind of man, though possessed of much larger faculties, proportioned to the grandeur of the work which he has executed. By this argument *a*

> *posteriori*, and by this argument alone, do we prove at once the existence of a Deity and his similarity to human mind and intelligence."[5]

Cleanthes observes that human artifacts and living beings share an essential characteristic, "the curious adapting of means to ends". Human artifacts exhibit signs of design, because they are the work of humans. Cleanthes argues by analogy: since living beings exhibit signs of design, like, though superior to, human artifacts, they must be the work of an intelligent being, like, though superior to, humans.

Hume's skeptic character Philo gives many counter-arguments to the Argument from Design, ranging from the weaknesses of the human analogy and the problem of infinite regress (who designed God?) to the possibility of order and design emerging from chaos. At the end, though, Philo agrees with Cleanthes, because he cannot take his own objections seriously:

> "What can the most inquisitive, contemplative, and religious man do more than give a plain, philosophical assent to the proposition, as often as it occurs; and believe, that the arguments, on which it is established, exceed the objections, which lie against it?"[6]

Darwin's theory of evolution provides a strong objection to the Argument from Design by convincingly showing how organisms seemingly adapted to their environment can emerge from a mindless evolutionary process through the principles of descent with modification and natural selection. Darwin showed that design, though it needs an explication, doesn't imply a designer.

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[5] Hume, David. *Dialogues Concerning Natural Religion*. First published 1779. London: Penguin Classics, 1990. p. 53
[6] Hume. p. 138

In his *Essay Concerning Human Understanding*, Locke wanted to prove *a priori* the primacy of Mind, which is essentially what the Argument from Design aims to infer *a posteriori*. Philo, in his final concessions, acknowledges as a legitimate conclusion:

> "if we are not contended with calling the first and supreme cause a GOD or DEITY, but desire to vary the expression; what can we call him but MIND or THOUGHT, to which he is justly supposed to bear a considerable resemblance?"[7]

Locke viewed his argument as a logical demonstration, deducing the existence of God from our own existence. Starting with the certain knowledge of our own existence, Locke first argues that there must be something eternal, because nothing can come from nothing. He then asks: "If, then, there must be something eternal, let us see what sort of Being it must be." [8] He reasons that "the eternal Being must necessarily be a cogitative Being" because "it is as impossible to conceive that ever bare incogitative Matter should produce a thinking intelligent Being, as that nothing should of itself produce Matter"[9]. In his proof, Locke takes for granted that mind cannot emerge from matter in order to conclude that mind must come first. Darwin's theory inverts the standard way of thinking about the mind, represented by Locke. According to Darwin, minds are a recent outcome of the mindless process of evolution.

Today, the debate about the emergence of mind from matter continues in the realm of the machines: can machines ever be intelligent or conscious? If human minds are the product of the mindless process of evolution, then intelligence and consciousness are

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[7] Hume. p. 128
[8] Locke, John. *Essay Concerning Human Understanding*. (First published 1690.) Book IV, Chapter x
[9] Locke.

reducible to matter in motion, which could be imitated in a machine. Trivially stated, machines can be intelligent, since we are intelligence machines. As Richard Dawkins puts it, we are "survival machines – robot vehicles blindly programmed to preserve the selfish molecules known as genes"[10]. Less trivially, the proponents of strong Artificial Intelligence (AI) believe that intelligence and consciousness could arise in sufficiently complex computational systems. This is a heated and fascinating debate, beyond the scope of this essay, with proponents and opponents of strong AI equally persuaded of their position.

For now, we can draw a parallel between the Tree of life as the shape of Darwin's evolutionary process and trees as the typical shape of the processes generated by AI search algorithms. This parallel is not a coincidence, because Darwin's idea of evolution can be cast in the mold of a generate-and-test AI algorithm: starting with a population, generate variations, select individuals according to some fitness function and iterate. The parallel has been fruitful in both directions, evolution having inspired its own brand of computational techniques including so-called genetic algorithms, and computational ideas having enriched our model of evolution.

Genetic algorithms are generate-and-test AI algorithms, which barrow concepts from evolutionary biology. The algorithm is seeded with an initial population of abstract individuals. At every iteration, individuals are selected stochastically according to their fitness to survive, reproduce, or die. During reproduction, the genotype of the selected individuals may mutate, or recombine as in sexual reproduction, to create the next

[10] Dawkins, Richard. The Selfish Gene (1976). New York: Oxford University Press, 1989. (p. vii)

generation. Generic algorithms explore a fitness landscape heuristically. In practice, it usually tricky to design a good fitness function, not surprisingly given the complex role of natural selection in evolution.

In the light of AI, the general idea of evolution is a search algorithm guided by natural selection, evolution as it's happening on Earth is a running process of this algorithm, and the Tree of Life is the shape generated by this process, showing the history of explorations.

> "The actual animals that have ever lived on Earth are a tiny subset of the theoretical animals that could exist. These real animals are the products of a very small number of evolutionary trajectories through genetic space. That vast majority of theoretical trajectories through animal space give rise to impossible monsters. Real animals are dotted around here and there among the hypothetical monsters, each perched in its own unique place in genetic hyperspace. Each real animal is surrounded by a little cluster of neighbors, most of whom have never existed, but a few of whom are its ancestors, its descendants and its cousins."[11]

Without the force of natural selection, the "evolutionary trajectories through genetic space" would drift randomly, accumulating change but not, plausibly, design. Natural selection leads to accumulation of design by allowing the "evolutionary trajectories through animal space" to not only drift but also lift in a fitness landscape, which, however, is constantly changing with the environment and ecosystem.

In conclusion, Darwin's Tree of Life conceptualizes the complexities of Darwin's theory and its revolutionary implications. The Tree of Life illustrates how the mindless little steps of evolution accumulate to create a seemingly magical adaptation of means to an end, the hallmark of design. Before Darwin described the mechanism by which design

[11] Dawkins, Richard. *The Blind Watchmaker*. (London: Longmans, 1986.) p. 73

could emerge from mindless steps, some philosophical ideas were inconceivable. For example, Locke's "proof" of the primacy of Mind stems from his impossibility of conceiving how mind could emerge from matter. By including man in the Tree of Life, Darwin gives the beginning of an answer – or rather the crux of an answer, growing in details over the next century and a half. For example, Darwin treated the mechanism of modification with descent as a black-box. Perhaps more telling, in his diagram, Darwin starts in the middle, showing how new species and groups can evolve from a set of existing species. He cautiously speculates that these species might themselves have evolved from a common ancestor, until the beginning of life. Today, scientists are still speculating on the origin of life, speculating on how a molecule gained the remarkable capability of producing copies of itself, thus triggering an increasingly and irregularly complex "struggle for life and survival of the fittest".