

Notes on the Origin of Evolutionary Computation

THE ORIGIN OF SPECIES

If during the long course of ages and under varying conditions of life, organic beings vary at all in the several parts of their organisation, and I think this cannot be disputed; if there be, owing to the high geometrical powers of increase of each species, at some age, season, or year, a severe struggle for life, and this certainly cannot be disputed; then, considering the infinite complexity of the relations of all organic beings to each other and to their conditions of existence, causing an infinite diversity in structure, constitution, and habits, to be advantageous to them, I think it would be a most extraordinary fact if no variation ever had occurred useful to each being's own welfare, in the same way as so many variations have occurred useful to man. But if variations useful to any organic being do occur, assuredly individuals thus characterised will have the best chance of being preserved in the struggle for life; and from the strong principle of inheritance they will tend to produce offspring similarly characterised. This principle of preservation, I have called, for the sake of brevity, Natural Selection.

Chapter 4: Natural Selection

In 1859 Charles Darwin published his book *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life*.

The shock waves produced by Darwin's revolutionary theory of evolution¹ are still reverberating within society at large, though science has by now come to terms with it.

One of the prominent offshoots of Darwinian evolution occurred almost a century later, with the advent of evolutionary algorithms in the 1950s. The basic idea, by now well entrenched within scientific and engineering lore, is both simple and ingenious: implementing within a computer a simulacrum of evolution by natural selection. The basic principle of evolutionary computation was enunciated by Darwin in his 1859 book: "... one general law, leading to the advancement of all organic beings, namely, multiply, vary, let the strongest live and the weakest die." (Chapter 7)

In the following article, I wish to go back to the origin of evolutionary computation, namely, *The Origin of Species*, with the aim being to expose some ideas that may be relevant to the field today. My strategy is simple: To illustrate each idea, I shall bring forth excerpts from the book, followed by a short annotation. This latter is intended neither to rephrase nor to explain—*The Origin of Species* is remarkable not only for its conceptual depth but also for its clarity of style. Rather, the anno-

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tations are intended to recast the preceding passage within the modern evolutionary computation framework. This article is not intended to serve as a review of work in the field of evolutionary computation—several good articles and books exist for this purpose. My aim is to recount my own views about some of the relationships between Darwin's *Origin* and modern evolutionary computation.

LARGE POPULATIONS

I must now say a few words on the circumstances, favourable, or the reverse, to man's power of selection. A high degree of variability is obviously favourable, as freely giving the materials for selection to work on; not that mere individual differences are not amply sufficient, with extreme care, to allow of the accumulation of a large amount of modification in almost any desired direction. But as variations manifestly useful or pleasing to man appear only occasionally, the chance of their appearance will be much increased by a large number of individuals being kept; and hence this comes to be of the highest importance to success.

Chapter 1: Variation Under Domestication

A large amount of inheritable and diversified variability is favourable, but I believe mere individual differences suffice for the work. A large number of individuals, by giving a better chance for the appearance within any given period of profitable variations, will compensate for a lesser amount of variability in each individual, and is, I believe, an extremely important element of success.

Chapter 4: Natural Selection

In these two passages, the first taken from the chapter on artificial selection (husbandry) and the second from the chapter on natural selection, Darwin argues in favor of large populations. This may well apply to evolutionary algo-

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rithms, the majority of which use very small populations (that is, on the order of a few hundred individuals). The continued increase in computational power serves to enfeeble the lack-of-computational-resources argument given to support the use of small populations. Large populations may thus be a simple remedy to the incessant concern of practitioners in the field—namely, the maintaining of variability—ultimately leading to better “organisms” (solutions).

NEUTRAL MUTATIONS, GENETIC DRIFT, AND PREADAPTATION

I am inclined to suspect that we see in these polymorphic genera variations in points of structure which are of no service or disservice to the species, and which consequently have not been seized on and rendered definite by natural selection, as hereafter will be explained.

Chapter 2: Variation Under Nature

Variations neither useful nor injurious would not be affected by natural selection, and would be left a fluctuating element, as perhaps we see in the species called polymorphic.

Chapter 4: Natural Selection

We are far too ignorant, in almost every case, to be enabled to assert that any part or organ is so unimportant for the welfare of a species, that modifications in its structure could not have been slowly accumulated by means of natural selection. But we may confidently believe that many modifications, wholly due to the laws of growth, and at first in no

way advantageous to a species, have been subsequently taken advantage of by the still further modified descendants of this species. We may, also, believe that a part formerly of high importance has often been retained (as the tail of an aquatic animal by its terrestrial descendants), though it has become of such small importance that it could not, in its present state, have been acquired by natural selection, a power which acts solely by the preservation of profitable variations in the struggle for life.

Chapter 6: Difficulties on Theory

One can see in these three passages references to phenomena that were elaborated over a century later by biologists, for example, neutral mutations, genetic drift, and preadaptation. Such phenomena are obviously of great interest to evolutionary-computation practitioners. (NB: Darwin considers both inter- and intra-species interactions. Though evolutionary algorithms are chiefly single-“species,” I believe this is not crucial for the account given herein, that is, the basic ideas still apply. In fact, this also raises the issue of designing multi-species, artificial-evolution scenarios).

COEVOLUTION

The dependency of one organic being on another, as of a parasite on its prey, lies generally between beings remote in the scale of nature. This is often the case with those which may strictly be said to struggle with each other for existence, as in the case of locusts and grass-feeding quadrupeds. But the struggle almost invariably will be most severe between the individuals of the same species, for they frequent the same districts, require the same food, and are exposed to the same dangers.

Chapter 3: Struggle for Existence

As the individuals of the same species come in all respects into the closest competition with each

other, the struggle will generally be most severe between them; it will be almost equally severe between the varieties of the same species, and next in severity between the species of the same genus. But the struggle will often be very severe between beings most remote in the scale of nature. The slightest advantage in one being, at any age or during any season, over those with which it comes into competition, or better adaptation in however slight a degree to the surrounding physical conditions, will turn the balance.

Chapter 14: Recapitulation and Conclusion

Darwin recounts here the coevolutionary nature of Nature—the “coadaptations of organic beings to each other” (Introduction chapter)—a theme that plays a pivotal role in Darwin’s theory, recurring throughout the book. Indeed, coevolution has been receiving increased attention in recent years within the evolutionary-computation community. These passages attest to the intricateness of this phenomenon—the degree to which inter- and intra-species competitions take place depends in complex ways on the amount of similarity (or in some cases dissimilarity) between the competitors. The coevolutionary aspect of nature was very succinctly worded by Darwin in Chapter 12, where he speaks of “organic action and reaction. . .” (Interestingly, this resembles Newton’s third law of motion—for every action, there is an equal and opposite reaction—a physical issue to which Darwin alludes in Chapter 3: “Throw up a handful of feathers, and all must fall to the ground according to definite laws; but how simple is this problem compared to the action and reaction of the innumerable plants and animals which have determined, in the course of centuries, the proportional numbers and kinds of trees now growing on the old Indian ruins!”)

PUNCTUATED EQUILIBRIA?

Not that in nature the relations can ever be as simple as this.

Battle within battle must ever be recurring with varying success; and yet in the long run the forces are so nicely balanced, that the face of nature remains uniform for long periods of time, though assuredly the merest trifle would often give the victory to one organic being over another.

Chapter 3: Struggle for Existence

We see nothing of these slow changes in progress, until the hand of time has marked the long lapses of ages, and then so imperfect is our view into long past geological ages, that we only see that the forms of life are now different from what they formerly were.

Chapter 4: Natural Selection

The slightest advantage in one being, at any age or during any season, over those with which it comes into competition, or better adaptation in however slight a degree to the surrounding physical conditions, will turn the balance.

. . . I do believe that natural selection will always act very slowly, often only at long intervals of time, and generally on only a very few of the inhabitants of the same region at the same time. I further believe, that this very slow, intermittent action of natural selection accords perfectly well with what geology tells us of the rate and manner at which the inhabitants of this world have changed.

Chapter 4: Natural Selection

One could possibly read “punctuated equilibria” into these passages, a controversial phenomenon evoked in the 1970s by paleontologists Eldredge and Gould, which has also been observed in some artificial-evolution experiments. Interestingly, in the last passage Darwin clearly relates “intermittent action” with the geological rec-

ord—the basis of Eldredge and Gould’s observations.

IMPLICIT VERSUS EXPLICIT FITNESS

Man selects only for his own good; Nature only for that of the being which she tends.

Chapter 4: Natural Selection

No country can be named in which all the native inhabitants are now so perfectly adapted to each other and to the physical conditions under which they live, that none of them could anyhow be improved. . .

Chapter 4: Natural Selection

Natural selection will not produce absolute perfection, nor do we always meet, as far as we can judge, with this high standard under nature.

Chapter 6: Difficulties on Theory

A major difference between artificial evolution, which is more akin to husbandry, and natural evolution is clearly stated above. This is largely related to the use of explicit fitness in evolutionary computation versus nature’s implicit fitness. The last two passages show that natural evolution does not optimize, as opposed to artificial evolution—which usually does (or at least has optimization as the underlying goal). One should note here, nonetheless, the few experiments that have tried to implement a more open-ended, implicit-fitness scenario (the most well-known example being Tom Ray’s Tierra world).

ARGUMENT FOR CROSSOVER

. . .that these facts alone incline me to believe that it is a general law of nature (utterly ignorant though we be of the meaning of the law) that no organic being self-fertilises itself for an eternity of generations; but that a cross with another individual is occasionally—perhaps at very long intervals—indispensable.

Chapter 4: Natural Selection

Decades before the advent of molecular biology, and based solely on phenotypical observations, Darwin concluded that crossover is of high utility. Practitioners in the domains of genetic algorithms and genetic programming, in which the use of crossover is ubiquitous, might take heart from its prominence in Darwin's text.

It should be noted that there are two different forms of recombination (crossover) in nature, which seem to get constantly conflated in the evolutionary-computation literature: *allelic recombination*, which occurs in the formation of a gamete *within* an individual, and *sexual recombination*, which occurs *between* individuals, when two gametes are fused into a zygote. By "crossing" Darwin was not referring to the former, unknown in his time, but rather to the latter, involving crossing—or mating—between individuals. (We note in passing that the evolutionary-computation literature often speaks of the importance of sex, though the traditional one-point crossover operator is more analogous to allelic recombination).

NO PURE ALTRUISM

What natural selection cannot do, is to modify the structure of one species, without giving it any advantage, for the good of another species; and though statements to this effect may be found in works of natural history, I cannot find one case which will bear investigation.

Chapter 4: Natural Selection

Natural selection will produce nothing in one species for the exclusive good or injury of another; though it may well produce parts, organs, and excretions highly useful or even indispensable, or highly injurious to another species, but in all cases at the same time useful to the owner.

Chapter 6: Difficulties on Theory

Simply put, pure altruism is not possible. Fitness assignment must always

entail some advantage to the evolving entity (be it the gene, the individual, or the group), an important consideration, especially where more complex coevolutionary scenarios are concerned.

ON COMPARING ALGORITHMS

But we may thus greatly deceive ourselves, for to ascertain whether a small isolated area, or a large open area like a continent, has been most favourable for the production of new organic forms, we ought to make the comparison within equal times; and this we are incapable of doing.

Chapter 4: Natural Selection

Just a reminder of an important criterion when comparing different evolutionary methodologies—"comparison within equal times"—which we *are* capable of doing where evolutionary algorithms are concerned.

NATURAL SELECTION VERSUS SEXUAL SELECTION

And this leads me to say a few words on what I call Sexual Selection. This depends, not on a struggle for existence, but on a struggle between the males for possession of the females; the result is not death to the unsuccessful competitor, but few or no offspring. Sexual selection is, therefore, less rigorous than natural selection.

Chapter 4: Natural Selection

Evolutionary computation concerns by and large the artificial analog of natural selection, with almost no attention given to the second determinant factor: sexual selection. This latter would be quite interesting to

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study in the context of evolutionary computation.

GEOGRAPHICAL CONSIDERATIONS

Isolation, also, is an important element in the process of natural selection. In a confined or isolated area, if not very large, the organic and inorganic conditions of life will generally be in a great degree uniform; so that natural selection will tend to modify all the individuals of a varying species throughout the area in the same manner in relation to the same conditions.

Chapter 4: Natural Selection

If, however, an isolated area be very small, either from being surrounded by barriers, or from having very peculiar physical conditions, the total number of the individuals supported on it will necessarily be very small; and fewness of individuals will greatly retard the production of new species through natural selection, by decreasing the chance of the appearance of favourable variations.

Chapter 4: Natural Selection

Geographical considerations permeate Darwin's book; indeed, two entire chapters are devoted solely to this issue (Chapters 11 and 12). In the above passages we note the importance of isolated niches, though not too small at that.

In an extremely small area, especially if freely open to immigration, and where the contest between individual and individual must be severe, we always find great diversity in its inhabitants.

Chapter 4: Natural Selection

On the other hand, if the niche is small, yet with a constant influx of new individuals, then selective pressure is maintained.

...that migration has played an important part in the first appear-

ance of new forms in any one area and formation. . .

Chapter 10: On the Geological Succession of Organic Beings

Widely-ranging species, abounding in individuals, which have already triumphed over many competitors in their own widely-extended homes will have the best chance of seizing on new places, when they spread into new countries. In their new homes they will be exposed to new conditions, and will frequently undergo further modification and improvement; and thus they will become still further victorious, and will produce groups of modified descendants.

Chapter 11: Geographical Distribution

Migration induces perennial competition. The use of niches in evolutionary algorithms can thus be seen not only to exhibit computational advantages (in terms of parallelism) but also more profound ones, deriving directly from Darwin's account.

Thus the high importance of barriers comes into play by checking migration. . .

Chapter 11: Geographical Distribution

If the difficulties be not insuperable in admitting that in the long course of time the individuals of the same species, and likewise of allied species, have proceeded from some one source; then I think all the grand leading facts of geographical distribution are explicable on the theory of migration (generally of the more dominant forms of life), together with subsequent modification and the multiplication of new forms. We can thus understand the high importance of barriers, whether of land or water, which separate our several zoological and botanical provinces.

Chapter 12: Geographical Distribution (continued)

This serves to emphasize the intricate interplay between isolation and migration—barriers should allow for some separation, though not a total one at that.

If, for instance, a number of species, which stand in direct competition with each other, migrate in a body into a new and afterwards isolated country, they will be little liable to modification; for neither migration nor isolation in themselves can do anything. These principles come into play only by bringing organisms into new relations with each other, and in a lesser degree with the surrounding physical conditions.

Chapter 11: Geographical Distribution

If a large body of individuals migrates from one niche to another, no fitness benefit will result since the status quo is maintained. One must strive to bring organisms "into new relations with each other. . ." In simple evolutionary-computation scenarios, the above passage might translate into a small number of migrating individuals.

To sum up the circumstances favourable and unfavourable to natural selection, as far as the extreme intricacy of the subject permits. I conclude, looking to the future, that for terrestrial productions a large continental area, which will probably undergo many oscillations of level, and which consequently will exist for long periods in a broken condition, will be the most favourable for the production of many new forms of life, likely to endure long and to spread widely. For the area will first have existed as a continent, and the inhabitants, at this period numerous in individuals and kinds, will have been subjected to very severe competition. When converted by subsidence into large separate islands, there will still exist many individuals of the

same species on each island: intercrossing on the confines of the range of each species will thus be checked: after physical changes of any kind, immigration will be prevented, so that new places in the polity of each island will have to be filled up by modifications of the old inhabitants; and time will be allowed for the varieties in each to become well modified and perfected. When, by renewed elevation, the islands shall be re-converted into a continental area, there will again be severe competition: the most favoured or improved varieties will be enabled to spread: there will be much extinction of the less improved forms, and the relative proportional numbers of the various inhabitants of the renewed continent will again be changed; and again there will be a fair field for natural selection to improve still further the inhabitants, and thus produce new species.

Chapter 4: Natural Selection

This passage gives rise to an interesting niche algorithm in which there is at first but a single "area," which is then divided into many smaller ones that are later reunited.

TIME CONSIDERATIONS

That natural selection will always act with extreme slowness, I fully admit. . . I do believe that natural selection will always act very slowly, often only at long intervals of time, and generally on only a very few of the inhabitants of the same region at the same time.

Chapter 4: Natural Selection

Though nature grants vast periods of time for the work of natural selection, she does not grant an indefinite period. . .

Chapter 4: Natural Selection

Evolution is slow. In many cases we may expect artificial evolution to exhibit

this same characteristic (though on different time scales). Thus, one should not despair if his or her 3-week simulation is still churning on.

One could argue here that evolution might at times be quite fast, for example, where bacteria and viruses are involved (which, by the way, were mostly unknown in Darwin's time). I should like to counterargue by saying that evolution is fast when the problem is easy. Novel forms of viruses can evolve quickly since often only a small series of mutations from an extant form is needed. I believe this holds for artificial evolution as well: Truly hard problems *do* require intensive computation and long evolution times; if not, then they were probably not that hard to begin with, or we have managed to render them easier by custom tailoring the evolutionary algorithm (the genomic representation or the genetic operators, for example).

ONTOGENY

There are many laws regulating variation, some few of which can be dimly seen, and will be hereafter briefly mentioned. I will here only allude to what may be called correlation of growth. Any change in the embryo or larva will almost certainly entail changes in the mature animal.

Chapter 1: Variation Under Domestication

Correlation of Growth. I mean by this expression that the whole organisation is so tied together during its growth and development, that when slight variations in any one part occur, and are accumulated through natural selection, other parts become modified. This is a very important subject, most imperfectly understood. . . any malconformation affecting the early embryo, seriously affects the whole organisation of the adult.

Chapter 5: Laws of Variation

But it is by no means obvious, on the ordinary view, why the struc-

ture of the embryo should be more important for this purpose than that of the adult, which alone plays its full part in the economy of nature.

Chapter 13: Mutual Affinities of Organic Beings: Morphology: Embryology: Rudimentary Organs

Ontogeny is the process by which a single mother cell, the zygote, gives rise, through successive divisions, to a complete organism, possibly containing tril-

One of the advantages of ontogeny concerns information compression—the ability to represent large phenotypes by much smaller genotypes.

lions of cells (for example, in humans). Darwin discussed this issue at some length in Chapter 13 (“Mutual Affinities of Organic Beings: Morphology: Embryology: Rudimentary Organs”). Essentially, ontogeny is the process that maps the genotype to the phenotype. This mapping is quite simple in most current evolutionary algorithms, though some more complex (ontogenetic) ones have been proposed. In such cases, one indeed notes the intricate intra-genomic relations, that is, “when slight variations in any one part occur. . . other parts become modified.” One of the advantages of ontogeny concerns information compression—the ability to represent large phenotypes by much smaller genotypes (as is the case, for example, with humans). Such compression leads, among others, to improved scalability. Note that it is the phenotype, that is, the result of the ontogenetic process, that “plays its full part in the economy of nature.”

ECONOMY OF STRUCTURE

I suspect, also, that some of the cases of compensation which have been advanced, and likewise some other facts, may be merged under a more general principle, namely, that natural selection is

continually trying to economise in every part of the organisation. If under changed conditions of life a structure before useful becomes less useful, any diminution, however slight, in its development, will be seized on by natural selection, for it will profit the individual not to have its nutriment wasted in building up an useless structure.

Chapter 5: Laws of Variation

Economy of structure may be observed when using evolutionary algorithms in which the genotypic structure is subject to change (for example, genetic programming)—*if* a cost is associated with structural complexity, as in nature (for example, a simple way of doing this in genetic programming would be by penalizing larger programs). Note that the case for economy is not clear-cut since “a part formerly of high importance has often been retained. . . though it has become of such small importance. . .” (Chapter 6).

VARIABILITY BEGETS VARIABILITY

Any part or organ developed to an extraordinary size or in an extraordinary manner, in comparison with the same part or organ in the allied species, must have gone through an extraordinary amount of modification since the genus arose; and thus we can understand why it should often still be variable in a much higher degree than other parts; for variation is a long-continued and slow process, and natural selection will in such cases not as yet have had time to overcome the tendency to further variability and to reversion to a less modified state.

Chapter 5: Laws of Variation

It is only in those cases in which the modification has been comparatively recent and extraordinarily great that we ought to find the generative variability, as it may be called, still present in a high degree.

Chapter 5: Laws of Variation

...and this implies in most cases that there has been recent variability; and therefore we might expect that such variability would often continue and be super-added to that arising from the mere act of crossing.

Chapter 8: Hybridism

This is interesting in that it suggests that variability itself is inheritable, and not a mere byproduct of genetic operations. Thus, one can try to engineer “generative variability” into one’s evolutionary algorithm.

LEVELS OF SELECTION

If we look at the sting of the bee... for if on the whole the power of stinging be useful to the community, it will fulfill all the requirements of natural selection, though it may cause the death of some few members.

Chapter 6: Difficulties on Theory

This difficulty, though appearing insuperable, is lessened, or, as I believe, disappears, when it is remembered that selection may be applied to the family, as well as to the individual, and may thus gain the desired end.

Chapter 7: Instinct

Darwin is discussing here an issue that has since received wide attention in biology—the level at which selection forces act. This can range from selection at the gene level (an extremist view, mainly championed by Richard Dawkins in *The Selfish Gene*), through the individual level, group level, species level, and higher. Some biologists have been advocating a more eclectic view that involves selection at several levels. This issue has been given little attention within the evolutionary-computation domain, with selection performed predominantly at the individual level.

CONDITIONS OF LIFE

It is an old and almost universal belief, founded, I think on a con-

siderable body of evidence, that slight changes in the conditions of life are beneficial to all living things.

Chapter 8: Hybridism

This may translate to slight changes in the fitness-function definition during the run of the evolutionary algorithm.

RARITY PRECEDES EXTINCTION

It is most difficult always to remember that the increase of every living being is constantly being checked by unperceived injurious agencies; and that these same unperceived agencies are amply sufficient to cause rarity, and finally extinction. We see in many cases in the more recent tertiary formations, that rarity precedes extinction...

Chapter 10: On the Geological Succession of Organic Beings

Where evolutionary algorithms are concerned, this may translate into a form of anti-elitist strategy—in order to maintain diversity one can retain (at least) some of these rare individuals, before they become extinct.

CONCLUDING REMARKS

The annotated *Origin of Species* presented above is but a sampling—the reader is encouraged to delve into the book and seek his own pearls. The gestalt effect of Darwin’s work from the standpoint of evolutionary computation is to remind us of the primitiveness of our algorithms with respect to nature. We may, from time to time, incorporate this feature or that, yet we still end up with but a simplified simulacrum. Furthermore, nature admits *all* the characteristics delineated here (and many more), which renders current evolutionary algorithms even further removed from reality.

Darwin’s book is by now 140 years old, naturally giving rise to the question of its relevance today. Surprisingly, it has withstood the test of time, not only as concerns the general framework, but also in many of the details (though ob-

viously not all). One major body of knowledge that was entirely lacking in Darwin’s time is the molecular underpinnings of evolution, which have been elaborated over the past 50 years. Where evolutionary algorithms are concerned this lack may have less dire consequences than for biology. One can view the *Origin* as a “high-level” account, with the lower level remaining unspecified. While this may cause biologists to frown, it perfectly serves practitioners in the field of evolutionary computation: These practitioners seek exactly such high-level ideas, which are then implemented in an entirely different medium than that of molecular biology. This also means that one is “permitted” to borrow an idea that has not withstood the (biological) test of time, if it proves useful in the digital medium.

It would perhaps be most fitting to end this account with Darwin’s own ending: “There is grandeur in this view of life, with its several powers, having been originally breathed into a few forms or into one; and that, whilst this planet has gone cycling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and most wonderful have been, and are being, evolved.”

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NOTE

1. In point of historical fact, one should refer to the Darwin-Wallace (or Wallace-Darwin) theory of evolution. As pointed out by Darwin himself in the introduction to his book: “. . . I have been urged to publish this Abstract. I have more especially been induced to do this, as Mr. Wallace, who is now studying the natural history of the Malay archipelago, has arrived at almost exactly the same general conclusions that I have on the origin of species.” Indeed, both Darwin and Wallace had presented their works to the Linnean Society on the same day.